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The Variable Speed
Induction Motor

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THE VARIABLE SPEED INDUCTION MOTOR

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Max Ross Hanna and Charles Dietrich Wesselhoeft

ENTITLED The Variable Speed Induction Motor

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF Bachelor of Science in Electrical Engineering.

Morgan Brooks.

HEAD OF DEPARTMENT OF Electrical Engineering.

3

C O N T E N T S .

PART I.

GENERAL TREATMENT OF THE VARIABLE
SPEED INDUCTION MOTOR.

PART II.

DESCRIPTION AND TEST OF A WESTINGHOUSE
TYPE "F" INDUCTION MOTOR.

PART I.

GENERAL TREATMENT OF THE VARIABLE SPEED INDUCTION MOTOR.

I. Present Status of the Variable Speed Induction Motor.

One of the most important problems now before the electrical engineering profession is the development of a successful variable speed induction motor. The importance of this problem becomes more evident daily, as the advantages of the constant speed induction motor come to be better understood. The absence of a commutator and the general simplicity of construction, together with its great overload capacity and durability, make the induction motor an almost ideal machine. And in many cases where constant speed is desirable it has displaced the direct current motor. Where variable speed is wanted, however, the direct current series motor has generally been preferred owing to its better efficiency. Could the efficiency and flexibility of the variable speed induction motor be increased, the entire science of electric traction would be revolutionized, making practicable cross country roads several hundred miles in length without the objectionable rotary converter substations. And it is this field of application that has directed the most attention toward the development of the variable speed induc-

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tion motor.

There are several methods of varying the speed of an induction motor.

The first method that would suggest its self is, changing the number of poles. This method is efficient but is not entirely satisfactory in that the range of speed is limited and the winding and switching device is complicated. For example a machine might have 1, 2, 3, 4, 5, or 6 pair of poles and at 60 cycles the corresponding speeds would be 3600, 1800, 1200, 900, 720 and 600 rev. per min. Difficulties in switching devices would be encountered however, in attempting to provide for more than three or four speeds. This method has been used to some extent in Europe.

A second method for changing the speed of an induction motor is by means of a series-parallel arrangement of the primary winding, or by changing the applied voltage. This method is lacking in both flexibility and efficiency and has found almost no application.

A third method is by introducing a variable resistance into the secondary circuit. The felxibility of this method is all that can be desired but the efficiency is low. In spite of their low efficiency however, motors controled by this method are being rapidly introduced for elevator and crane service.

A fourth method, known as concatenation, consists in supplying the primary of one motor from the secondary of another, the two being mechanically connected. Under these conditions the motors run at about half speed. This system is quite efficient but lacks flexibility. It has found some application.

None of the methods for varying the speed of induction motors that have suggested so far, have combined felxibility and good efficiency.

II. Theory of Speed Control of Induction Motors.

The ordinary induction motor, although sometimes called asynchronous, operates at nearly synchronous speed. When it is loaded down the slip increases, and with this increase in slip, the secondary induced E. M. F. and current increase. This increase in current produces increased torque until a certain value of slip is reached where the torque will decrease with increasing slip, because of the effects of magnetic leakage and low power factor of the secondary circuit. With ordinary values of secondary resistance this point of maximum torque is reached at five to twenty per cent. slip. The torque is of course very small at starting. The ordinary induction motor is evidently anything but suitable to operate at variable speeds.

The speed of an induction motor can be varied by one of two general methods or by a combination of the two, either the synchronous speed or the slip or both may be changed. The various methods of accomplishing these results have already been pointed out.

When the synchrounous speed is varied, the motor operates under much the same conditions as a constant speed motor with the same synchronous speed; hence, it may have very good efficiency but usually has poor starting torque.

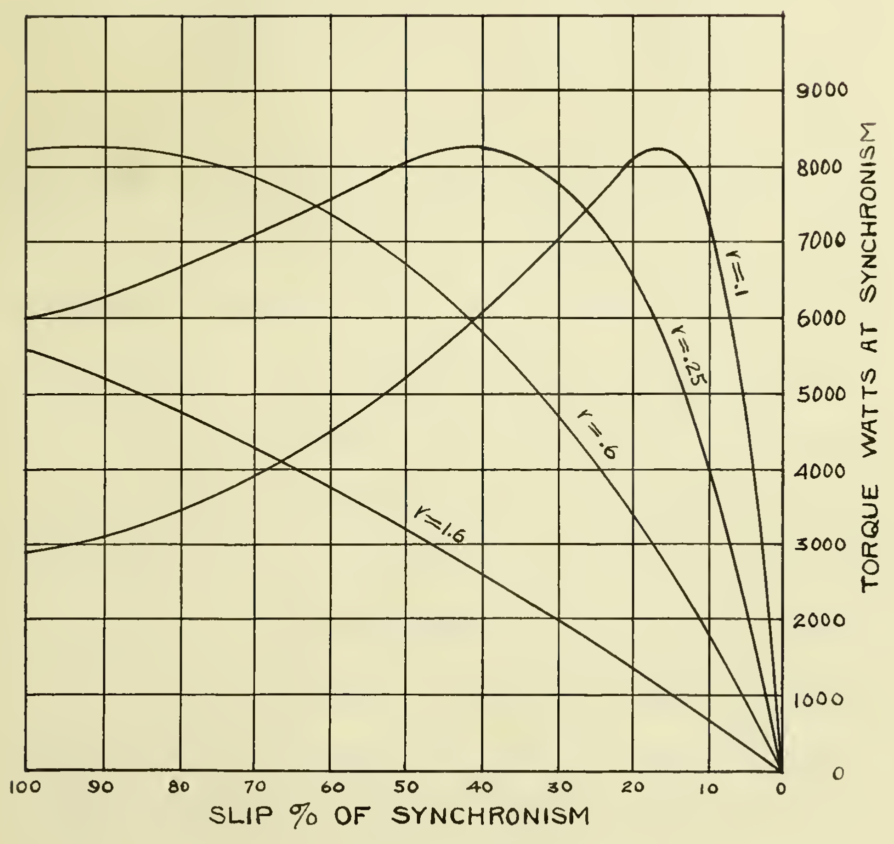
If the slip of an induction motor is varied by any means except one which takes an electrical output from the secondary, the

method will be necessarily inefficient. The secondary input is the product of synchronous speed and torque while the mechanical output is the product of actual speed and torque. The power represented by the product of slip and torque is a loss, unless it is recovered as an electrical output.

The first slip method referred to in the preceding chapter consisted in changing the applied voltage. Let us for the present neglect the effects of magnetic leakage and secondary inductance. Suppose the motor to be developing a given torque at a given speed and voltage, if the voltage is halved the field density will be halved and the secondary current necessary to produce the given torque will be doubled. The secondary induced voltage and current are, under the assumed conditions, proportional to the field density and slip. Hence to produce the given torque, the slip must be four times as great, that is, at constant torque the slip varies inversely as the square of the voltage. The effect of magnetic leakage and secondary inductance would be to increase the slip still more.

Rheostatic control may be analyzed in the following manner. Neglecting leakage and inductance, as before, the torque is proportional to the secondary current and the secondary voltage varies as the slip. Hence at constant torque the slip is proportional to the secondary resistance. The leakage and inductance would increase the slip, especially at high values of slip and low values of resistance. The relation between torque and speed with different values of secondary resistance is shown in figure 1, which is taken from Steinmetz' "Elements of Electrical Engineering". Speed variation would be effected by changing from one curve to the other.

Concatenation, as has been previously stated, consists in supplying one motor from the secondary of another, and rigidly coup-



9000
8000
7000
6000
5000
4000
3000
2000
1000
0
TORQUE WATTS AT SYNCHRONISM
r=1
r=.25
r=.6
r=1.6
100
90
80
70
60
50
40
30
20
10
0
SLIP % OF SYNCHRONISM

Fig. 1.

ling the two. This is a combination of the two general methods of varying speed. The slip of the first motor is varied by taking an electrical output from its secondary, while the synchronous speed of the second is varied by changing the frequency of supply. Since the frequency of supply of the second motor is equal to the slip of the first, the second motor tends to run at a speed equal to the slip of the first. If N is the speed of the second motor and S, the slip of the first, both expressed in per cent. of synchronism, then the motors tend to approach a condition, $N = S$, but since they are rigidly coupled $N+S = 1$, therefore $N = .5$, or the motors will tend to run at half synchronous speed. When a load is applied the speed will fall off slightly. The input of the second motor is the product of the slip and torque of the first less the copper loss of the secondary, thus at half synchronism the input of the second motor is approximately equal to the output of the first; and the two motors will divide the load almost equally. If any number of motors, N, were concatenated the sum of the slips of all of the Motors and the speed would be equal to unity and the motors would tend to run at one N,th. synchronism. The efficiency of a concatenated couple is about the same as that of a similar motor with half the number of poles.

In general the slip of an induction motor can be made to assume any value with a given torque, provided the losses or the sum of the losses and the electrical output of the secondary are made to equal the product of that torque and slip.

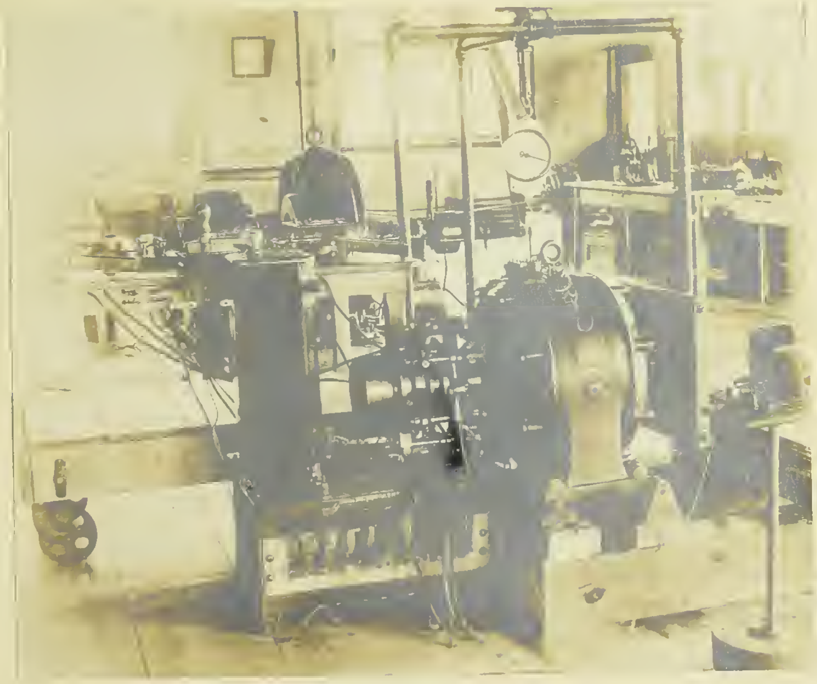
P A R T II.

DESCRIPTION AND TEST OF A WESTINGHOUSE TYPE "F" INDUCTION MOTOR.

I. Motor and Apparatus.

The Westinghouse Type "F" induction motor is a variable speed motor, of the rheostatic control class designed for crane, elevator and hoist service. A photograph of the motor and the testing apparatus used in this thesis is given on page 9 . The motor is two-phase, 60 cycle, has a synchronous speed of 1200 rev. per min. and is designed for 220 or 110 volts.

A photograph of the primary alone is given on page 10 . As is seen in the photograph, the winding is uniformly distributed around the circumference in slots. There are 72 slots and six poles, making 12 slots per pole; or 6 slots per pole, per phase. The winding per phase for each pole consists of 6 coils connected in series and lying in successive slots. Fig. 2 is a diagram of part of the stator winding. The coils have a span of 8 slots and are made up of 7 turns of two strands of No. 14 B. & S . gauge wire. The terminals of the winding for each phase of each pole are brought out and connected to lugs on top of the machine, thus making it possible to connect up the winding in any desired way. With all the windings of



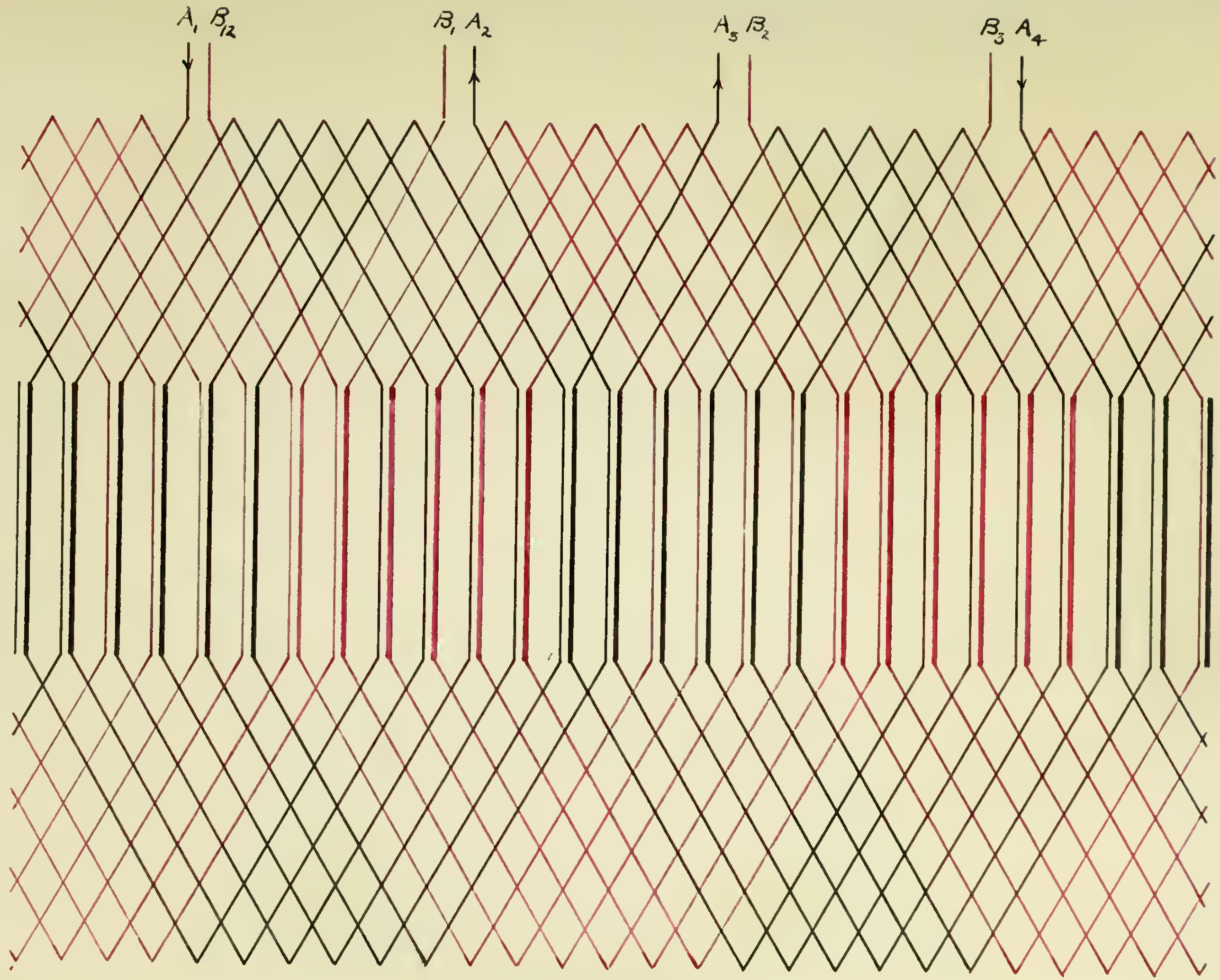


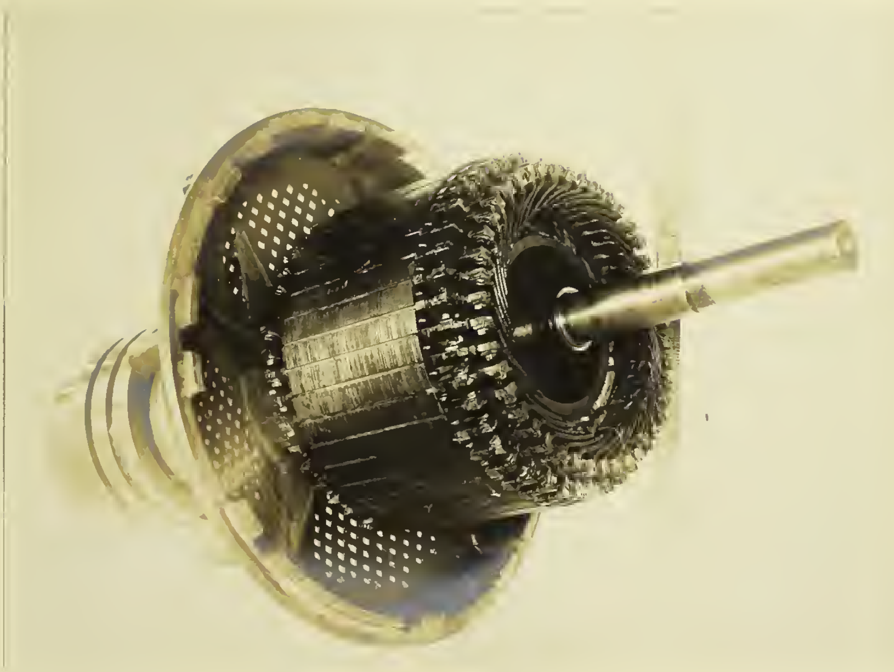
FIGURE 2.
DIAGRAM OF STATOR WINDING
WESTINGHOUSE TWO-PHASE TYPE "F" INDUCTION MOTOR.

one phase connected in series the applied voltage should be 220 volts. The winding can also be connected for 110 volts, 67 volts and 33 volts, by placing either three, two or one pole winding in series. In the following tests 110 volts was used, it being the best available voltage.

Assembled Data on Stator.

Bore of stator	12.55"
Length of stator iron parallel to shaft	6.42"
No of slots	72
Slots per pole	12
Slots per pole per phase	6
Depth of slots	1.28"
Width of slots	0.24"
Width of teeth	0.30"
No. of conductors	1008

A photograph of the rotor together with the slip rings and one end plate is shown on page 13 . The rotor has 43 slots, each slot containing two rectangular copper conductors. Fig. 3 is a diagram of the rotor winding, which is three-phase, star connected. With 86 conductors all of the legs of the star can not be equal. The conductors are arranged so that there are 30 to one leg, and 28 to the two other legs. This is done to guard against having the rotor lock and the machine acting as a transformer.



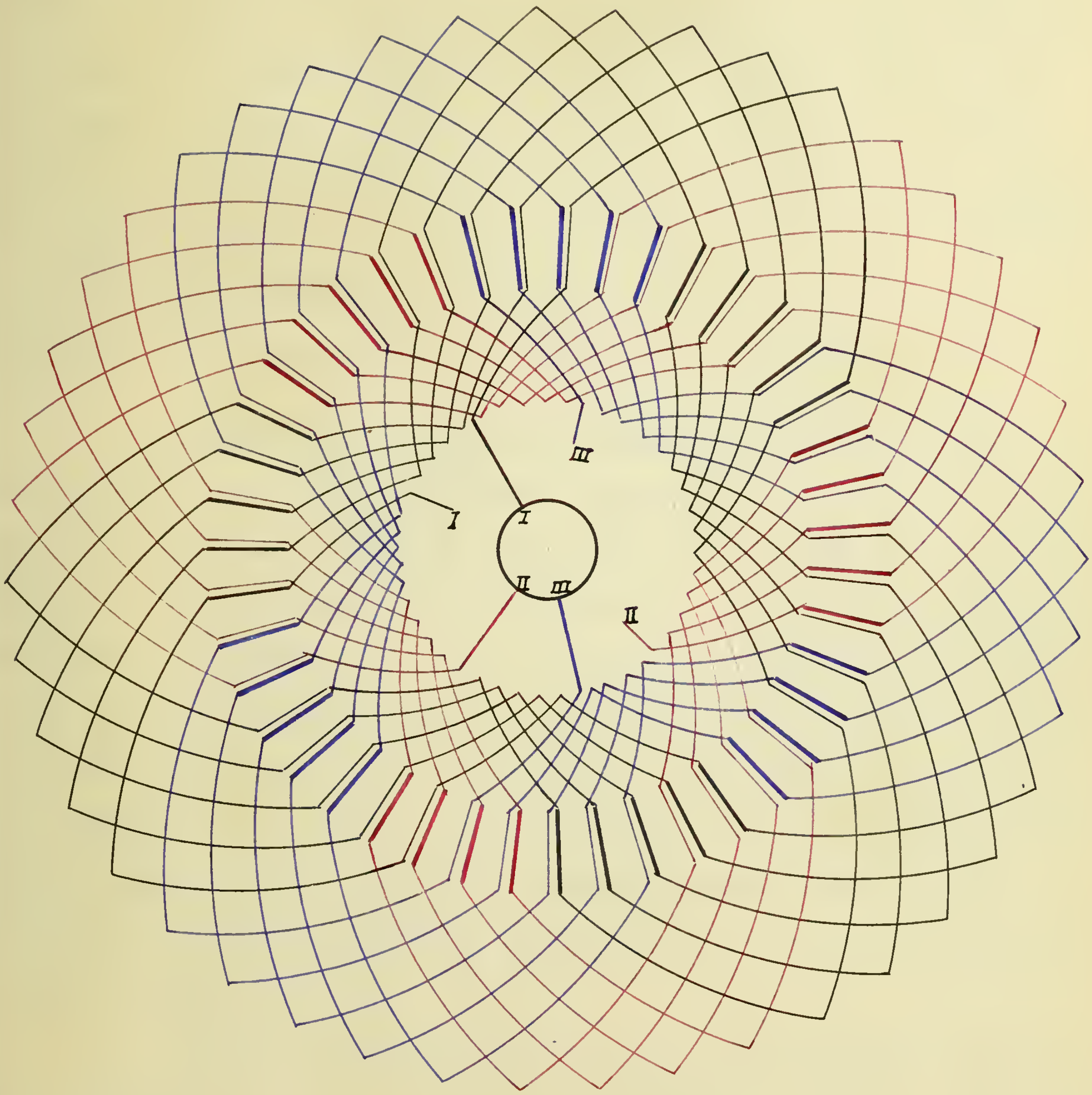


FIGURE 3.
DIAGRAM OF ROTOR WINDING.
WESTINGHOUSE TYPE "F" MOTOR.

Assembled Data on Rotor.

Outside diameter of core discs	12.46
Length of rotor iron between heads	6.18"
No. of slots	43
Depth of slots	1.37"
Width of slots at base	0.38"
No. of conductors in slot	2
Depth of each conductor	0.50"
Width of each conductor	0.25"
Number of conductors	86

The resistance used for regulation in the secondary circuit is made up of cast iron grids, compactly set up in an outside iron frame and insulated from each other and from the outer frame by asbestos. These grids are divided equally into three lengths and permanently connected in a star. The free ends of the star are connected by means of heavy leads to three sets of two carbon brushes, that rest on the three slip rings on the rotor shaft, to which the rotor winding is connected. Leads from the free end and four intermediate points of each leg of the iron resistance star are brought out to the controller, which is mounted on the end of the frame of the iron resistance.

A diagram of the iron resistance and controller connections is shown in Fig. 4. The controller has six steps. The first step throws the main two-phase current onto the primary of the machine. The successive steps of the controller gradually cut out the resistance, by decreasing the length of the legs of the star, until

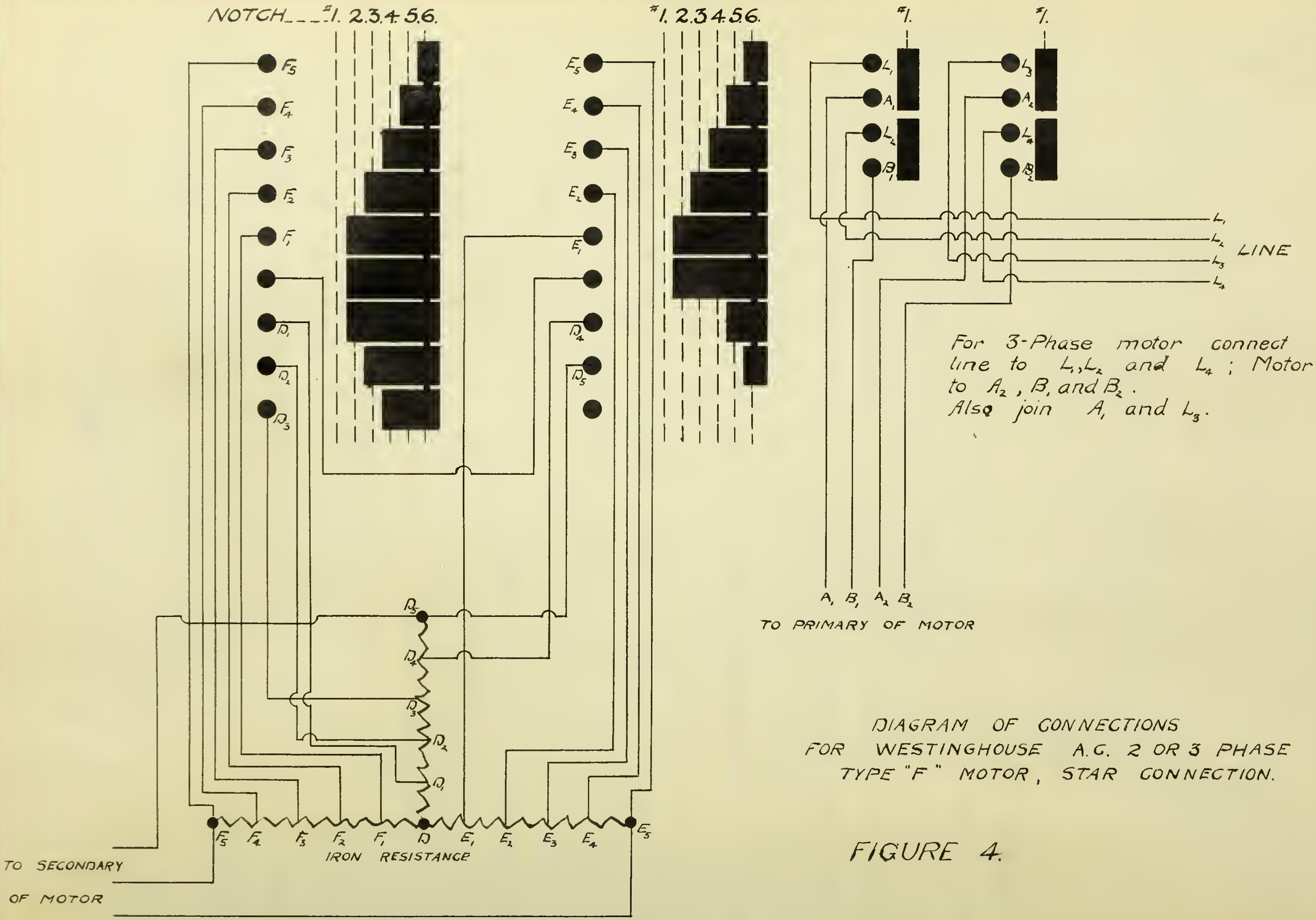


DIAGRAM OF CONNECTIONS
FOR WESTINGHOUSE A.C. 2 OR 3 PHASE
TYPE "F" MOTOR, STAR CONNECTION.

FIGURE 4.

the sixth notch of the controller which short circuits the leads from the rotor slip rings.

For convenience and to save time in making connections before each run a table was wired up for two-phase currents, as shown in Fig. 5. In wiring the table precaution was taken against inductive action of the main leads under the table, on the instruments, by running the two leads of each phase parallel and close together as much as possible. Switch, M, short circuits the ammeters and current coils of the wattmeters, thus protecting these instruments when there are large fluctuations of current or when the machine is taking heavy currents, as at starting. Two, two-way switches were used in connection with the voltmeters, one connection throwing the voltmeter on the main leads before going through the main switch, making it possible to read the voltage before the machine is thrown on; and the other connection putting the voltmeter on the leads just before leaving the table, for the machine, thus avoiding the resistance drop through the instruments and table connections when the machine is loaded, and giving us practically the voltage at the terminals of the machine. The table was connected in between the controller and the machine, the fuses, FF, protecting the apparatus against excessive currents.

In all power tests the power was absorbed by a Prony brake.

The speed was measured by a tachometer, belted to the shaft of the motor. An adjustable resistance was placed in series with the voltmeter of the tachometer and the resistance adjusted until the voltmeter read directly on its scale the rev. per min. of the motor.

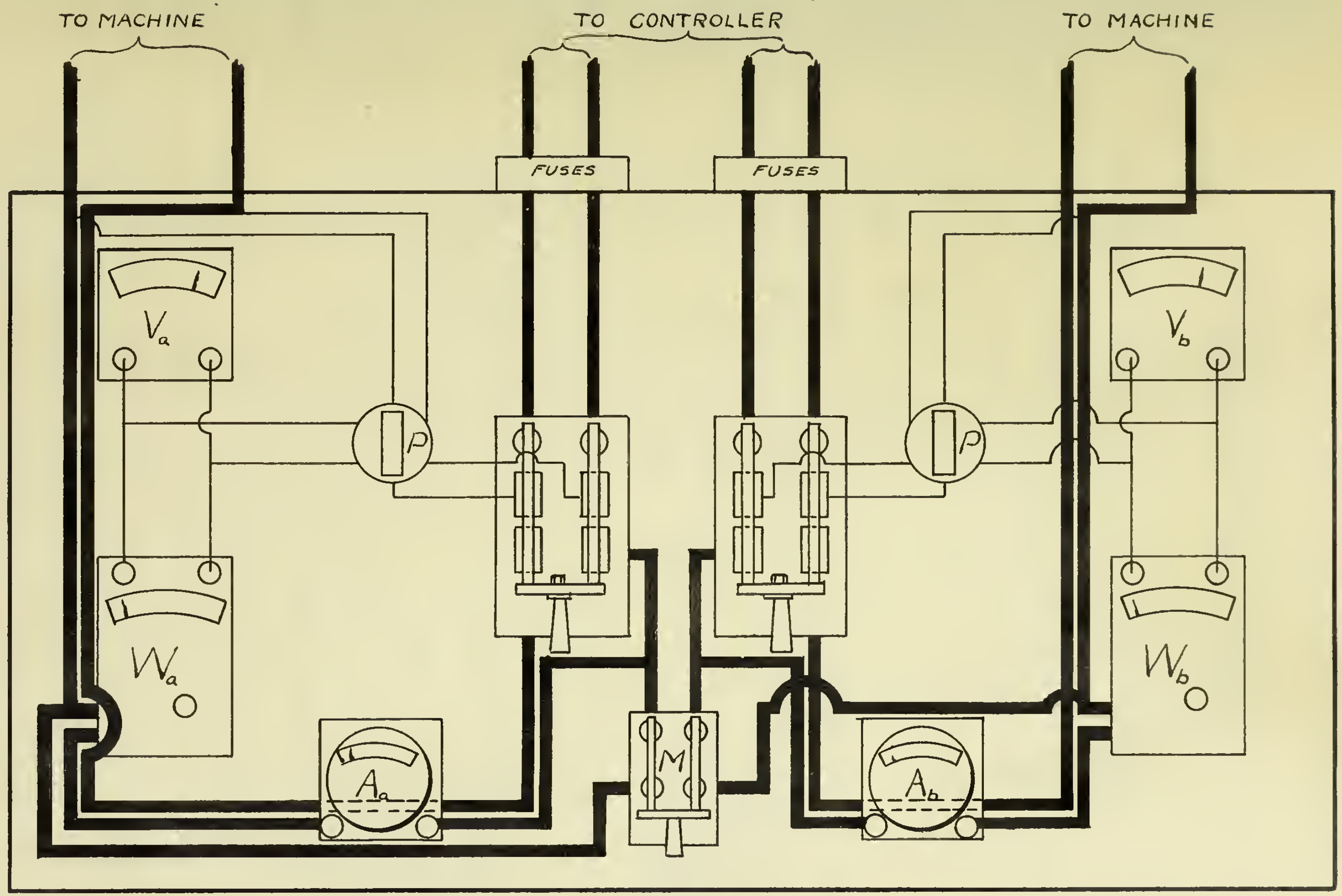


FIGURE 5.

TABLE INSTRUMENTS AND CONNECTIONS.

II. Description of Tests.

OPERATION.--Test runs were made on each of the six notches at a constant applied E.M.F. of 110 volts. The following readings were taken: E.M.F. current and input of each of the two phases, the frequency, speed and pull on the brake. The data from these runs is tabulated on pages 28 to 33 .

ROTOR CURRENT.--Test runs were made with ammeters in two of the three phases of the rotor. The readings taken were; applied voltage, frequency, rotor current speed and pull on the brake. Five points were taken on each notch. The range of the ammeters was not great enough to measure the higher values of rotor current. The data from these runs is tabulated on page 34 .

COPPER LOSSES.--The resistances of both phases of the stator and each phase of the rotor, between rings, were measured hot and cold. The resistance of the brushes and brush contacts were measured, hot, while the motor was being driven at full speed by means of a D.C. motor. The resistance of each phase of the controling resistance and leads was measured for each notch, cold. All resistance measurements were made by the fall of potential method. The resistances as computed from these measurements are given on page 44 .

IRON LOSSES.--To obtain the iron losses three sets of readings were taken with the rotor circuit open, first with the rotor stationary, second, while the rotor is being revolved in synchronism, and third while the rotor is being revolved backward at a speed equal to synchronism. The readings taken were; E.M.F., cur-

rent and input of each phase and the frequency. A shunt motor directly coupled was used to revolve the rotor. The data are given on page 45 .

FRICTION.--The friction loss of the motor was measured by driving it from a shunt motor and measuring the input and losses of the shunt motor. The friction losses were also computed from the operation curves as will be explained later. The results of this test are tabulated on page 46 .

III. Calculation of Results.

(A). OPERATION.--The calculations for the operation curves consisted in correcting the instrument readings, computing power factors for each phase, reducing pounds pull on the brake to torque in pound-feet, computing outputs in kilowatts from torque and R.P.M., and calculating efficiencies. The results are tabulated on pages 28 to 34 , and the curves are plotted on pages 35 to 43 .

(B). SEPARATION OF LOSSES.--For the separation of losses five values of torque were selected and all losses computed for these points.

COPPER LOSSES.--The values of resistances were used as measured hot, except in the case of the iron rheostat where the resistances were measured cold and corrected for the temperature rise, as measured by means of a thermometer. The temperature coefficient was taken as .004 for one degree centigrade. The secondary circuits were star-connected and the resistances were measured between two of the terminals. An average value was found for the resistance from the center to one of the terminals, and the total loss taken as three times the product of this resistance and the square of the current in one branch. The values of stator and rotor current were read from the operation curves.

IRON LOSSES.--The stator iron loss, which was assumed to remain constant, was computed by subtracting the copper loss from the

input of the stator when the rotor circuit was open and the rotor was being driven in synchronism.

The rotor iron loss was computed on the assumption that the flux density remained constant. The iron loss of the rotor at 60 cycles was found by subtracting the iron loss of the stator from the total iron loss of the motor with the rotor stationary on open circuit. The eddy current loss of the rotor at 60 cycles was computed by subtracting the electrical input of the rotor stationary from the electrical input of the rotor when it was driven backward at a speed equal to synchronism. When the rotor is stationary its frequency is 60 cycles and the total iron loss is supplied electrically. When it is being driven backward its frequency is 120 cycles and half of the iron loss is supplied electrically and half mechanically. With the frequency doubled the hysteresis loss is doubled, but only half of this double loss is supplied electrically, hence the elctrical input due to hysteresis loss is the same in both cases. The total eddy current loss is quadrupled at the double frequency but only half of this or twice the eddy current loss at 60 cycles is supplied electrically. Hence the increase in electrical input when the rotor is driven backward at synchronous speed is equal to the eddy current loss at 60 cycles. The hysteresis loss in the rotor at 60 cycles was found by subtracting the eddy current loss from the total iron loss in the rotor. The speeds corresponding to the torques for which the losses were computed were read from the operation curves, and the rotor iron losses computed. If H is the hysteresis loss at 60 cycles and E the eddy current loss at 60 cycles; the hysteresis loss at N revolutions per minute is equal to $H(1-\frac{N}{1200})$ and the eddy current loss is equal to $E(1-\frac{N}{1200})^2$.

FRICTION.--The friction loss was determined in two ways, by means of a calibrated motor and by extending some of the operation curves. The loss was calculated from the calibrated motor method by subtracting the stray power and copper losses of the D. C. motor from its input. The value of counter torque due to friction was obtained by extending the curve of rotor current backward until it cut the torque axis. At this point the rotor is in synchronism and the friction only, is being supplied by the negative torque represented by the intercept of the rotor current line on the torque axis. The values of friction torque obtained by the two methods checked fairly well. The value obtained by extending the curves was used. The friction losses at different speeds were calculated upon the assumption that the counter torque of friction remained constant at all speeds.

IV. Discussion of Results.

Since this motor is of the type used for elevator and crane service, its performance would probable be stated as a certain torque at a certain speed, instead of so many horse power; hence all curves were plotted on a torque base.

(A). OPERATION CURVES.--The operation curves are shown on pages 35 to 43 . They consist of speed, input, output, efficiency, power factor, primary current and secondary current, all plotted on a torque base. These curves were plotted for each of the six notches of the controler. The speeds, outputs and efficiencies for all notches were each assembled on a torque base.

The input curves are approximately straight lines and all have about the same slant; showing that the input is proportional to the torque regardless of speed or secondary resistance.

The power factors corresponding to a given torque are nearly equal for all notches, as might be expected from the fact that the magnetizing current is nearly constant and the input is the same on each notch.

The output curves show a very great reduction in capacity with the higher values of secondary resistance. The maximum output for the first notch is .4 kilowatt and for the last notch, 4.8 kilowatts. The output at the point of maximum efficiency is 3. kilowatts.

The maximum efficiencies for the first and sixth notches respectively are, 28.5% and 70.5%. For each notch the maximum effi-

ciency occurs at a torque approximately equal to half the torque at which the maximum output is developed.

The assembled speed curves indicate excellent speed control. For values of torque up to 12 pound feet six speeds are available, for values up to 35 pound feet, at least three speeds are possible. The maximum torque on each notch is developed at standstill, but the friction changing from motion to rest causes the available torque to fall off slightly just before standstill. The speed curve for the last notch intersects the torque axis at nearly right angles, indicating that if the resistance were any lower, the maximum torque would be developed while running. The speed curves for the first three notches are nearly straight while those for the last three are more or less curved, indicating that the effect of leakage and secondary inductance is slight for the first notches and quite considerable for the last.

The rotor currents were plotted as far as the values were measured, that is, up to 100 amperes. Up to this value the curves were nearly straight but curved up slightly. For the first three notches the 100 amperes covered nearly the whole range, but for the last three, the curves had to be extended. In extending the curves the effects of leakage and secondary inductance were taken into consideration by bending the curves upward.

The stator current curves bend up slightly on the first notches and quite decidedly for the last. The values of stator current are nearly the same on all notches for corresponding values of torque.

(B). SEPARATION OF LOSSES.--The tabulated data for the separation of losses are shown on pages 47 and 48 , and the curves

on pages 49 to 54 . The following are the loss curves plotted for each notch: stator copper loss, rotor copper loss, loss in regulating resistance, stator iron loss, rotor iron loss, friction loss, and the sum of all of these losses. The output and the sum of the output and the total losses, or the computed input, together with the speed and actual input, were plotted with the loss curves.

For the first four notches it will be seen that the loss in the external resistance is nearly the whole loss for the higher values of torque. On the sixth notch the losses in the external resistance and the stator and rotor resistances are nearly equal. The stator and rotor copper losses constitute a very small per cent. of the total losses on the first four notches. On the last two notches, however, they are a considerable proportion of the total.

At the higher speeds, the friction loss constitutes a large portion of the total losses, but as the speed decreases and the torque increases, it loses its importance. The greater part of this friction is due to the six heavy brushes on the collector rings.

The stator iron loss, which was considered constant, is a very small per cent. of the total loss except at no load, when it constitutes about 15%. The rotor iron loss is practically zero at no load and quite small at full load, so that it has almost no effect on the efficiency.

For all notches except the first two, the input as computed from the losses agrees fairly well with the observed input.

V. Conclusion.

The general results of the test show that the motor has a low average efficiency, fairly good power factor, good starting torque, and excellent speed control. In such service as driving cranes, elevators and hoists, the efficiency is of minor importance, while the starting torque, speed control, and general reliability are of the greatest importance. For this class of work, this motor should prove entirely satisfactory.

No.	E_a	I_a	W_a	$P.F._a$	E_b	I_b	W_b	$P.F._b$	R.P.M.	Torque	Output	Input	Eff. %
1	110.4	12.25	.475	0.356	110.2	12.25	0.416	0.308	952	0.0	0	0.891	0
2	110.4	12.80	.530	0.375	110.7	12.55	0.478	0.344	900	1.414	0.180	1.008	17.9
3	110.4	13.2	.687	0.471	110.2	13.25	0.633	0.434	781	2.828	0.314	1.320	23.8
4	109.6	13.8	.780	0.516	110.2	13.80	0.746	0.491	707	4.242	0.425	1.526	27.8
5	110.2	14.5	.890	0.558	110.0	14.4	0.842	0.532	611	5.656	0.491	1.732	28.4
6	109.9	15.3	1.010	0.602	109.5	15.25	0.942	0.568	510	7.070	0.512	1.958	26.3
7	110.2	16.1	1.125	0.635	110.0	16.2	1.070	0.602	405	8.484	0.488	2.195	22.2
8	110.4	16.7	1.230	0.668	110.2	17.0	1.170	0.625	284	9.898	0.399	2.40	16.6
9	110.0	17.9	1.328	0.675	110.0	17.9	1.264	0.643	170	11.31	0.273	2.592	10.5
10	110.6	18.6	1.400	0.682	110.7	18.7	1.323	0.640	90	12.72	0.163	2.723	6.0
11	109.9	18.5	1.400	0.689	109.9	18.5	1.318	0.648	56	12.72	0.101	2.718	3.7
12	109.6	18.5	1.400	0.691	109.2	18.5	1.318	0.653	42	12.72	0.076	2.738	2.8
13	110.0	18.7	1.410	0.686	110.2	18.7	1.328	0.645	38	12.89	0.069	—	2.5
14	110.0	—	—	—	110.0	—	—	—	17	13.02	—	—	—
15	110.4	—	—	—	110.2	—	—	—	10	13.30	—	—	—
16	110.4	18.9	1.420	0.681	110.2	19.45	1.446	0.675	drifting	.290	ε	2.866	ε

TEST RUN NOTCH #1

No	E_a	I_a	W_a	P.F.$_a$	E_b	I_b	W_b	P.F.$_b$	R.P.M	Torque	Output	Input	Eff. %
1	110.2	11.9	0.385	0.294	110.2	11.95	0.45	0.342	1029	0	0	0.835	0
2	109.9	13.0	0.623	0.437	110.2	12.95	0.68	0.477	890	2.828	0.350	1.303	27.5
3	109.8	14.5	0.878	0.551	110.0	14.45	0.95	0.598	745	5.656	0.568	1828	32.8
4	110.0	16.4	1.110	0.615	109.2	16.20	1.17	0.662	602	8.484	0.725	2 28	31.8
5	110.4	18.4	1.350	0.665	110.2	18.25	1.405	0.700	440	11.31	0.707	5.755	25.6
6	110.4	20.3	1.565	0.690	110.2	20.5	1.635	0.724	270	14.14	0.542	3.200	15.0
7	109.8	22.3	1.760	0.720	110.1	22.75	1.860	0.743	58	6.94	0.140	3.620	4.3
8	110.0	22.6	1.846	0.743	110.0	23.4	1.953	0.760	dr.	13.52	0	3.800	0
9	109.9	12.0	0.406	—	109.2	11.95	0.48	—	1005	0	0	—	0
10	110.0	—	—	—	110.0	—	—	—	St.	15.47	0	—	0

TEST RUN. NOTCH 2.

No.	E_a	I_a	W_a	$P.F._a$	E_b	I_b	W_b	$P.F._b$	R.P.M.	Torque	Output	Eff. %	Input
1	110.1	12.75	0.34	0.242	110.4	11.65	0.328	0.255	1088	0	0	0.668	0
2	110.2	12.65	0.565	0.406	110.4	12.45	0.565	0.411	1004	2828	0.403	1.130	35.7
3	110.0	14.00	0.82	0.536	109.2	13.45	0.812	0.553	955	5.656	0.766	1.632	47.0
4	110.4	15.65	1.10	0.637	110.1	15.40	1.055	0.623	812	8.484	0.876	2.155	40.7
5	110.4	17.30	1.328	0.695	110.1	17.15	1.268	0.671	742	11.31	1.190	2.596	46.0
6	110.2	19.5	1.590	0.740	109.7	19.50	1.52	0.711	626	14.14	1.255	3.11	40.4
7	109.8	21.9	1.850	0.770	109.2	22.10	1.76	0.730	482	16.94	1.160	3.61	32.2
8	110.1	24.8	2.122	0.778	109.8	24.9	2.042	0.748	350	19.80	0.982	4.174	23.5
9	110.6	27.2	2.372	0.790	110.1	27.3	2.293	0.762	199	22.62	0.727	4.665	15.0
10	110.2	28.75	2.49	0.788	109.8	28.7	2.422	0.770	113	24.03	0.386	4.912	7.8
11	109.8	30.8	2.655	0.785	109.5	30.0	2.55	0.777	0	21.55	0	5.205	0

TEST RUN. NOTCH 3.

No	E_a	I_a	W_a	$P.F._a$	E_b	I_b	W_b	$P.F._b$	R.P.M	Torque	Output	Input	Eff %
1	110.0	11.9	0.41	0.314	109.2	11.95	0.435	0.334	1140	0	0	0.845	0
2	110.0	13.3	0.745	0.510	110.2	13.65	0.810	0.540	1068	4.242	.643	1.555	41.4
3	109.9	15.9	1.13	0.647	110.0	15.90	1.17	0.670	1000	8.484	1.204	2.300	52.4
4	109.9	18.9	1.51	0.728	110.0	19.00	1.57	0.752	918	12.72	1.660	3.080	53.9
5	110.2	22.9	1.94	0.770	109.2	23.00	1.985	0.790	816	16.94	1.964	3.925	50.1
6	110.4	26.4	2.305	0.792	110.2	26.6	2.385	0.814	715	21.20	2.150	4.690	45.8
7	110.3	32.5	2.850	0.795	110.2	32.4	2.905	0.815	535	26.87	2.040	5.755	35.5
8	110.4	38.7	3.40	0.796	110.2	38.3	3.370	0.799	290	32.53	1.338	6.770	19.8
9	109.9	45.0	3.92	0.793	109.4	44.1	3.675	0.762	dr.	33.73	ε	7.595	ε

TEST RUN. NOTCH 4

No.	E_a	I_a	W_a	$P.F._a$	E_p	I_b	W_b	$P.F._b$	R.P.M.	Torque	Output	Input	Eff. %
1	110	11.0	0.45	0.372	110	12.0	0.405	0.307	1178	0	0	0.855	0
2	110	14.1	0.97	0.625	110	13.8	0.880	0.530	1118	5.656	0.897	1.850	48.5
3	110	18.0	1.45	0.732	110	17.8	1.405	0.718	1070	11.62	1.720	2.855	60.3
4	110	22.6	2.02	0.813	110	22.6	1.95	0.785	1012	16.94	2.440	3.970	61.5
5	110.3	28.0	2.51	0.814	110	27.8	2.46	0.805	944	22.63	3.030	4.970	61.0
6	110.4	33.7	3.10	0.833	110	33.9	2.98	0.800	870	28.28	3.490	6.08	57.4
7	110.1	40.8	3.71	0.826	110	41.2	3.62	0.782	754	33.94	3.630	7.33	49.5
8	109.7	49.2	4.34	0.804	110	50.0	4.30	0.720	580	39.60	3.260	8.64	37.7
9	109.9	65.1	5.18	0.794	109.9	64.1	5.07	0.720	150	45.25	0.932	10.25	9.1
10	109.9	68.2	5.18	0.692	110	65.3	5.36	0.747	dr.	42.42	ε	10.54	ε

TEST RUN. NOTCH 5.

No.	E_a	I_a	W_a	$P.F._a$	E_b	I_b	W_b	$P.F._b$	R.P.M	Torque	Output	Input	Eff. %
1	110.0	11.2	0375	0.304	109.9	11.3	0.35	0.282	1191	0	0	0.725	0
2	110.1	4.9	1.09	0.665	109.8	15.3	1.13	0.673	1131	8.48	.362	2.22	6.7
3	110.3	24.0	2.11	0.798	110.1	23.7	2.14	0.820	1064	19.80	3.00	4.25	70.7
4	109.4	32.7	3.0	0.840	110.1	32.8	3.01	0.834	998	28.28	4.00	6.01	66.5
5	110.3	46.3	4.32	0.846	110.0	46.1	4.28	0.845	852	39.60	4.78	8.60	55.0
6	110.8	60.7	5.16	0.774	109.5	60.2	5.05	0.767	705	45.25	4.53	10.21	44.4
7	110.8	73.8	5.82	0.712	110.0	72.7	5.625	0.704	506	48.10	3.46	11.445	32.5

TEST RUN NOTCH 6

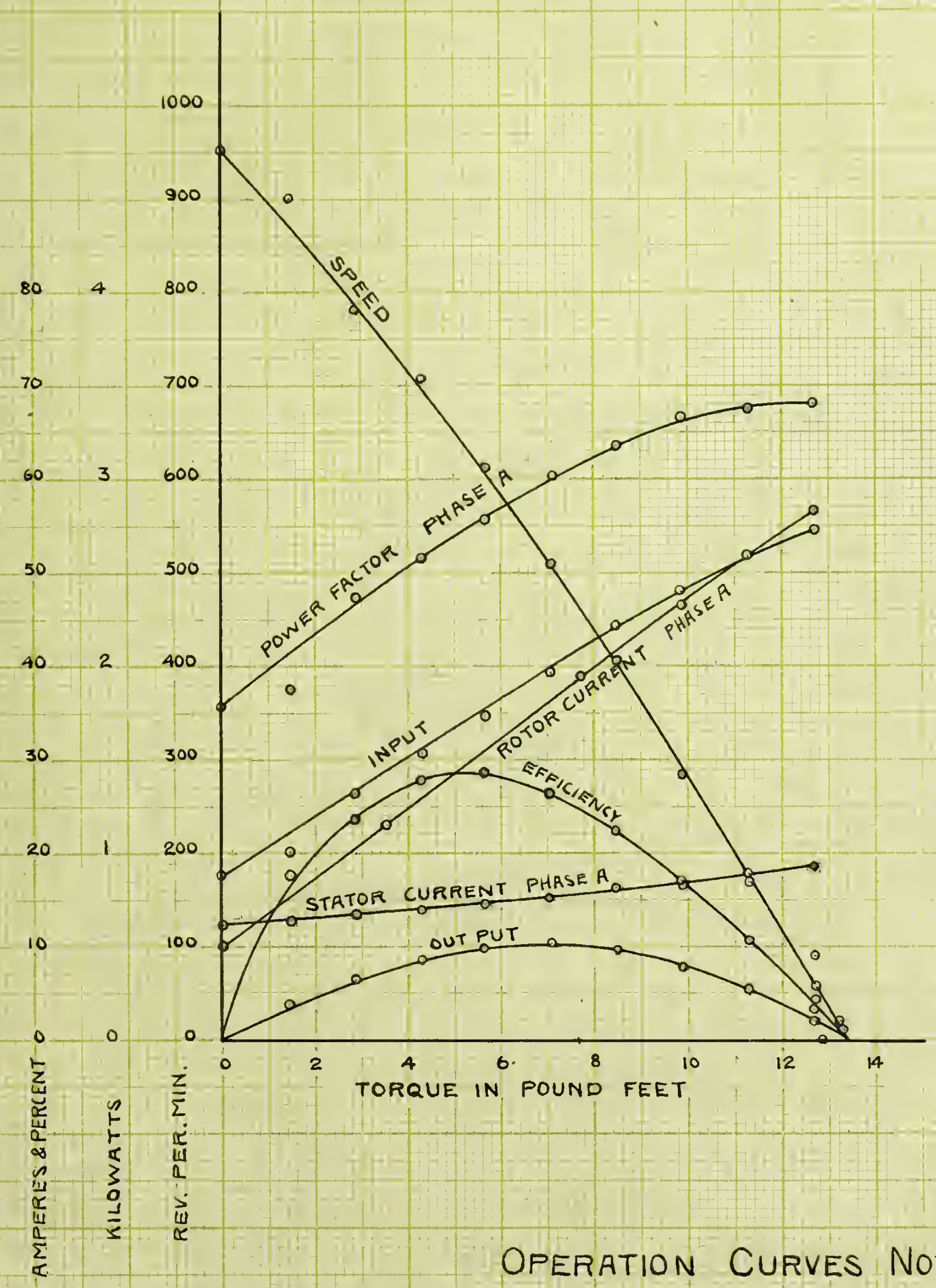
NOTCH 1.

I_a	I_b	R.P.M.	Torque
11.3	10.0	1010	0
23.0	23.0	810	3.53
38.1	39.0	476	7.78
45.5	46.5	288	9.90
55.2	56.7	83.2	12.70
NOTCH 2.			
11.8	10.9	1050	0
26.4	27.0	830	4.24
38.0	39.0	686	7.78
57.8	58.1	390	12.70
77.0	77.0	58	16.94
NOTCH 3.			
12.3	2.2	1105	0
34.0	34.7	889	6.19
52.4	54.0	730	11.30
65.4	65.1	606	14.11
92.5	92.5	31.6	20.36

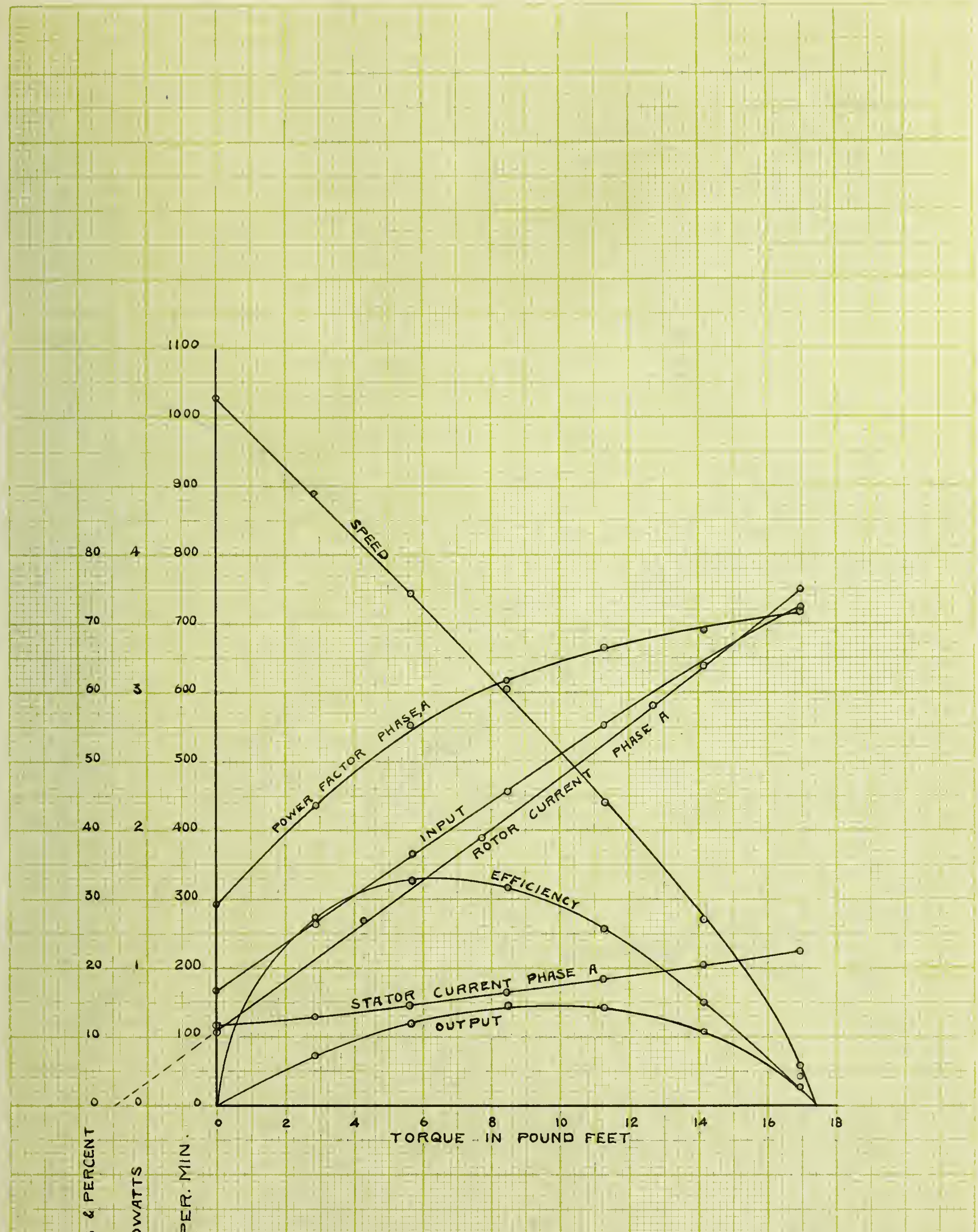
NOTCH 4.

I_a	I_b	R.P.M.	Torque
11.3	11.0	1138	0
31.3	33.0	1012	5.91
48.4	50.0	922	10.06
65.5	66.0	824	14.11
90.0	90.0	706	19.75
NOTCH 5.			
.2	11.2	1151	0
32	31.5	1059	5.65
56	54.5	991	11.30
69	67.5	950	14.11
93	93	882	9.75
NOTCH 6.			
12.0	11.2	1148	0
32.5	33.8	1074	5.65
57.5	57.5	1029	11.30
68.0	70.0	010	4.11
90.0	95.0	978	9.75

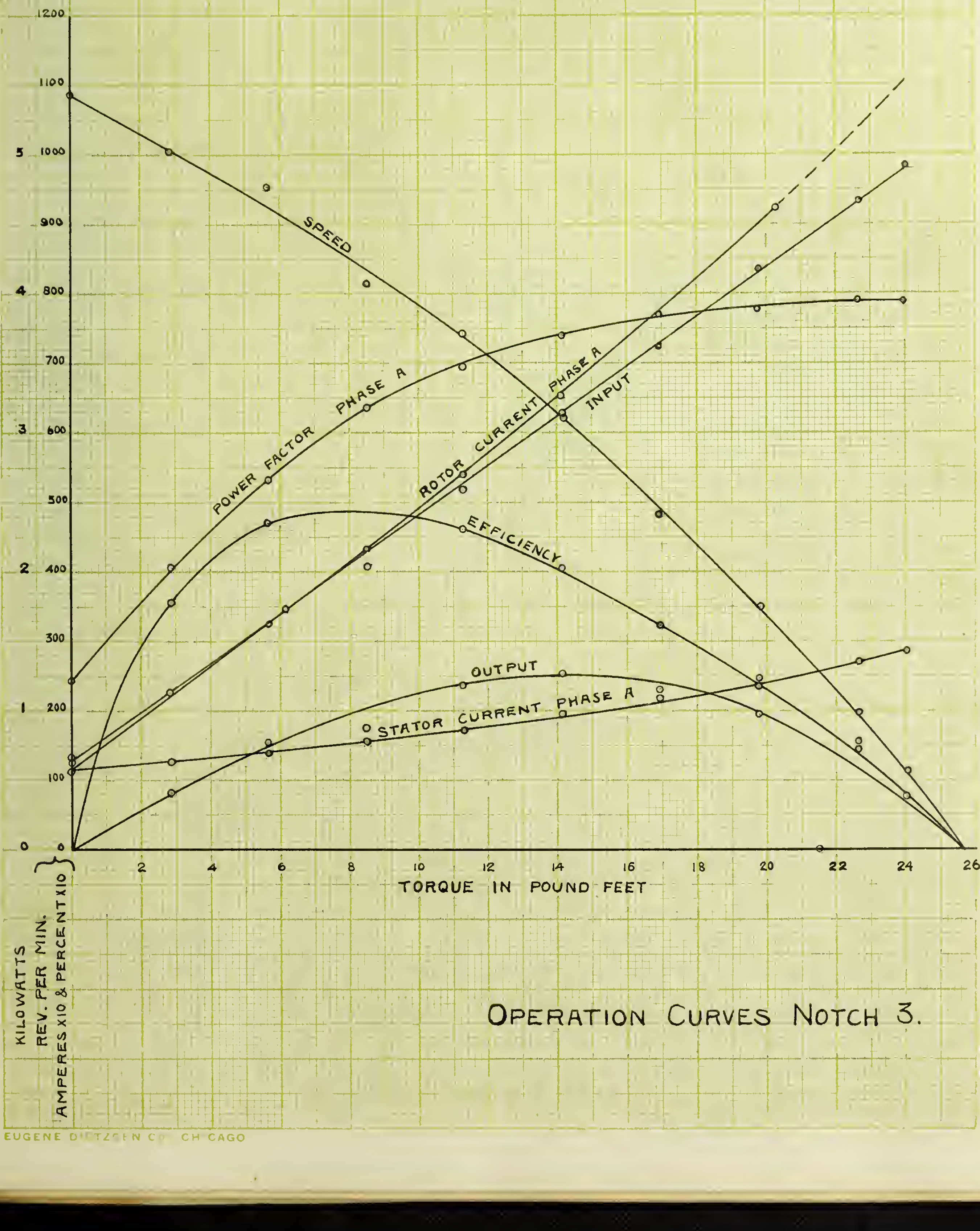
ROTOR CURRENT.



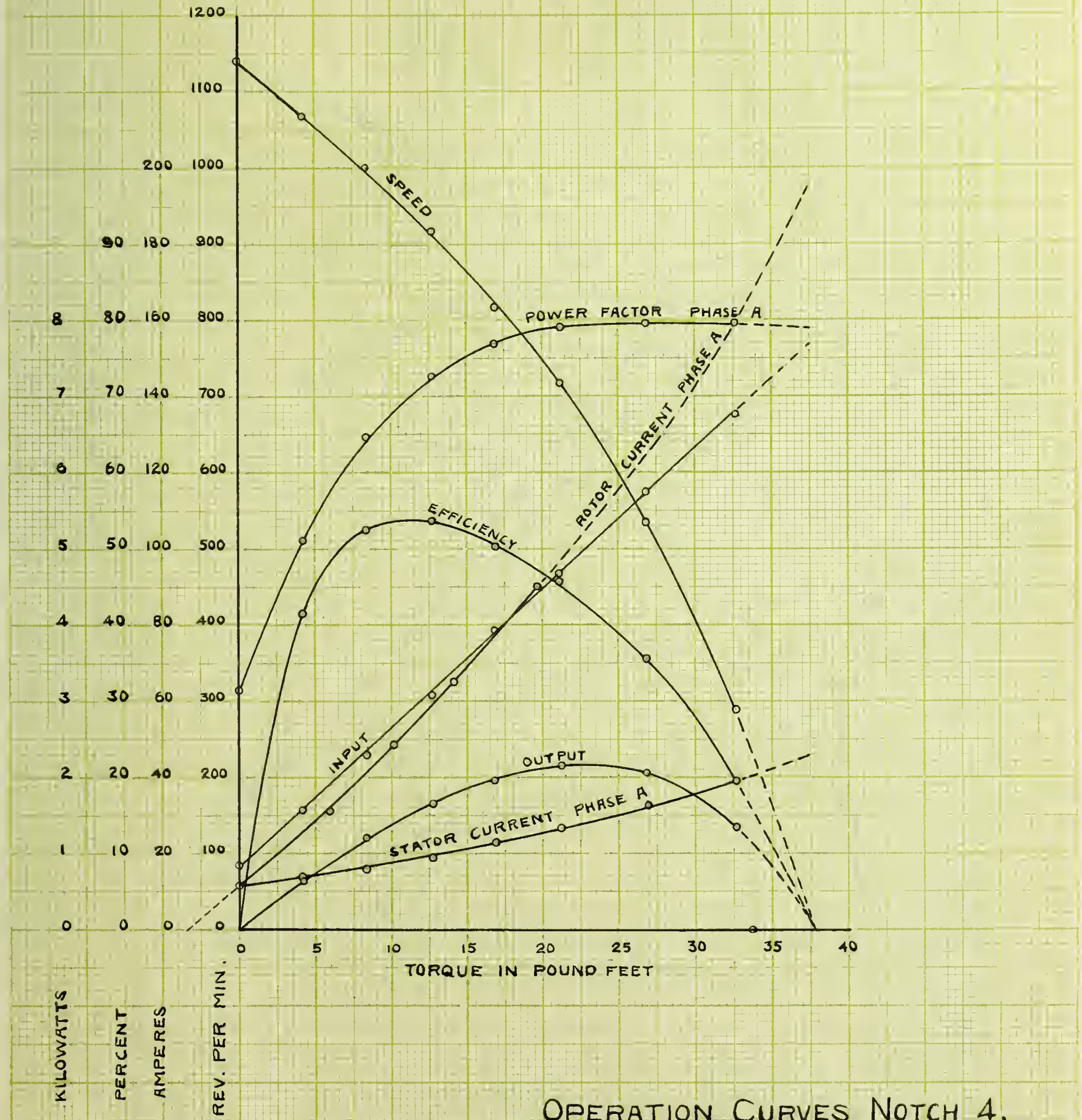
OPERATION CURVES NOTCH I.



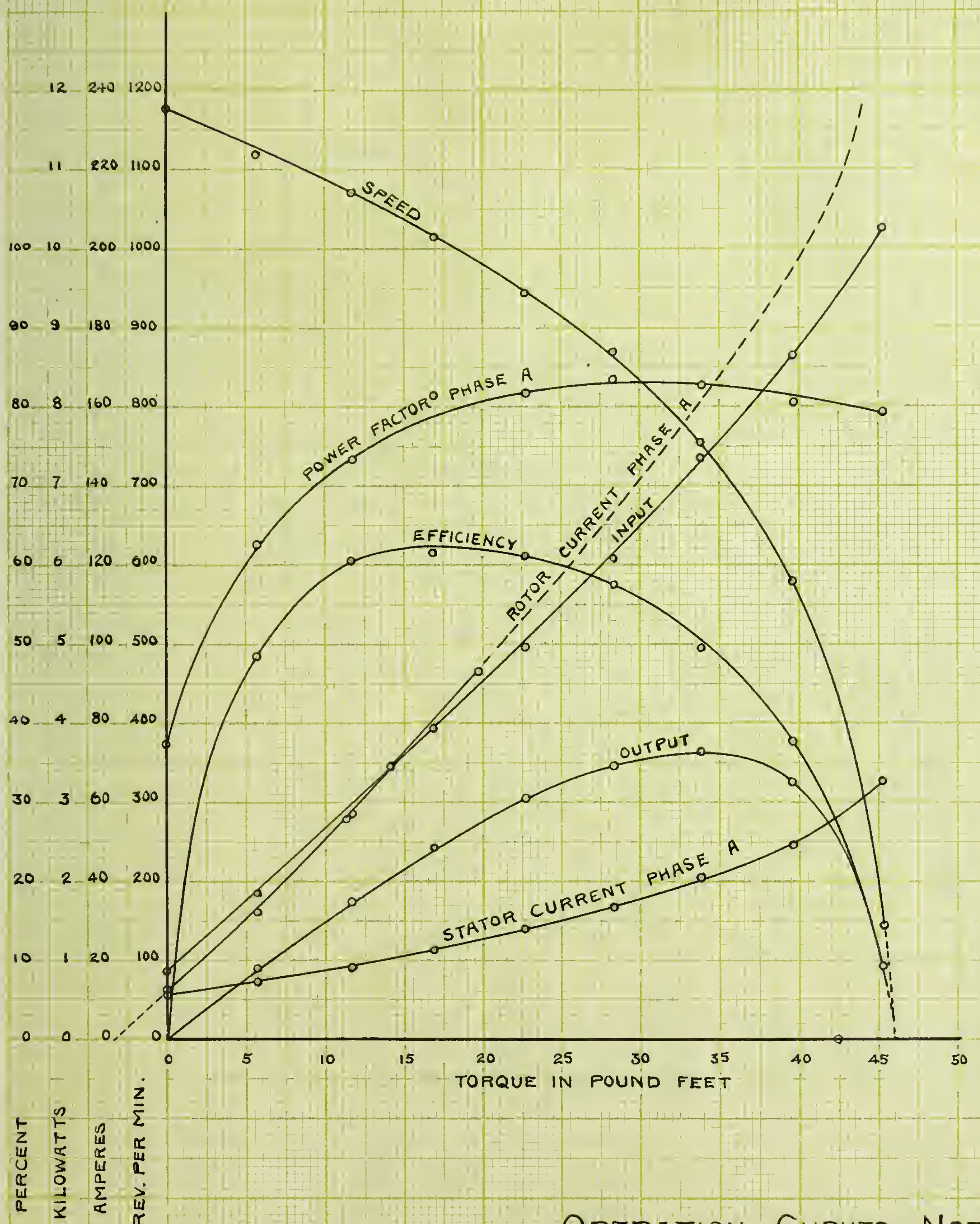
OPERATION CURVES NOTCH 2.



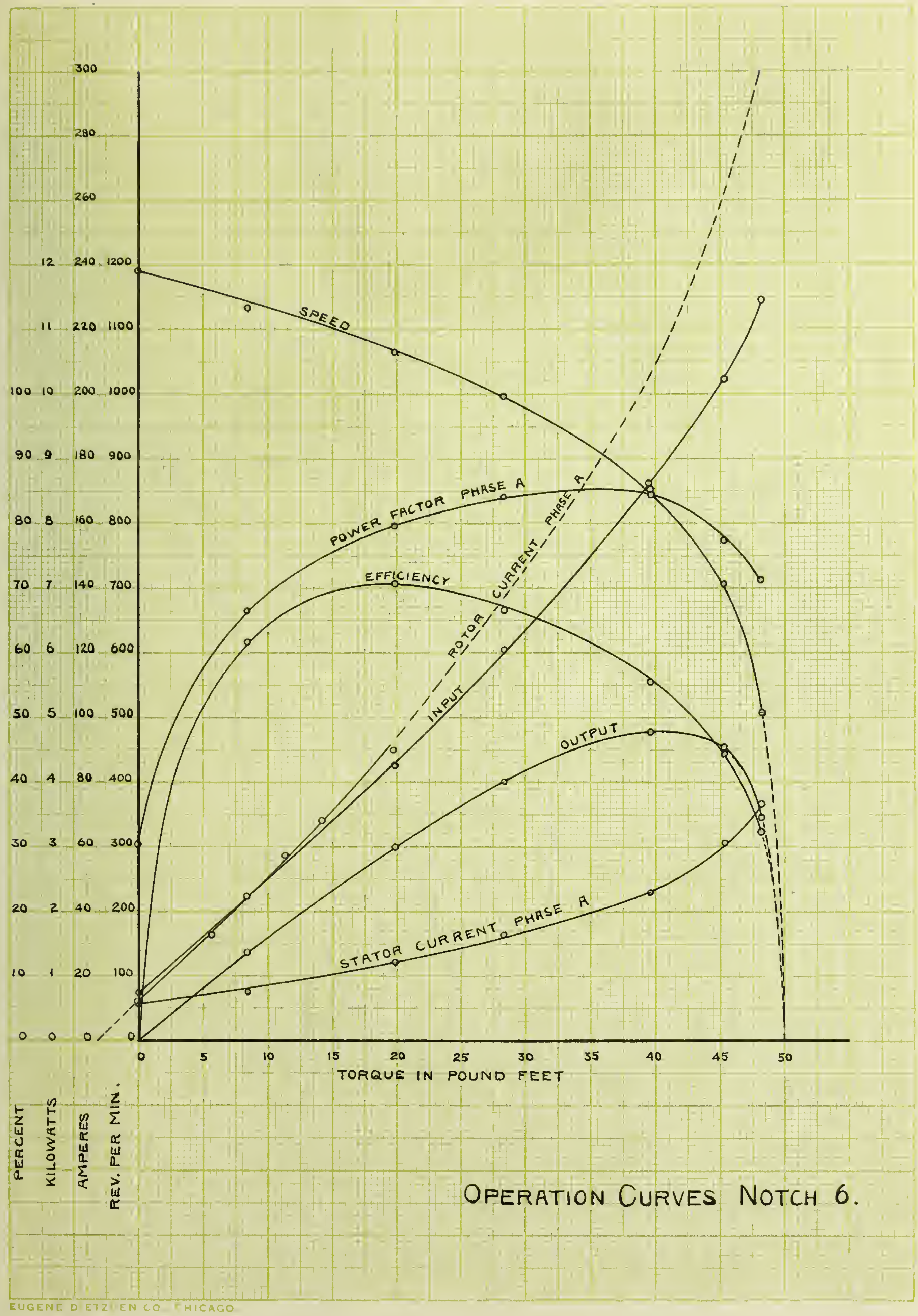
OPERATION CURVES NOTCH 3.



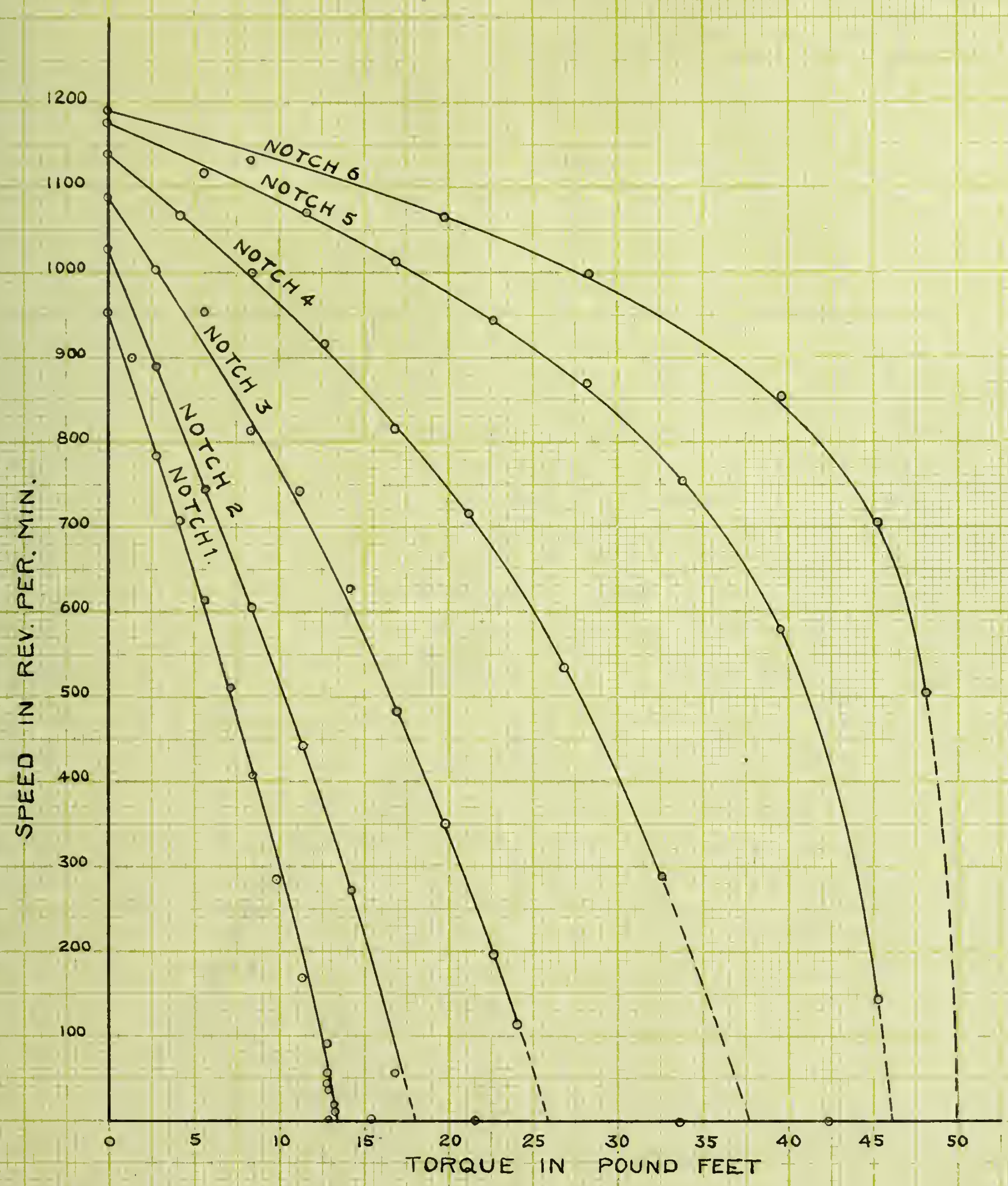
OPERATION CURVES NOTCH 4.



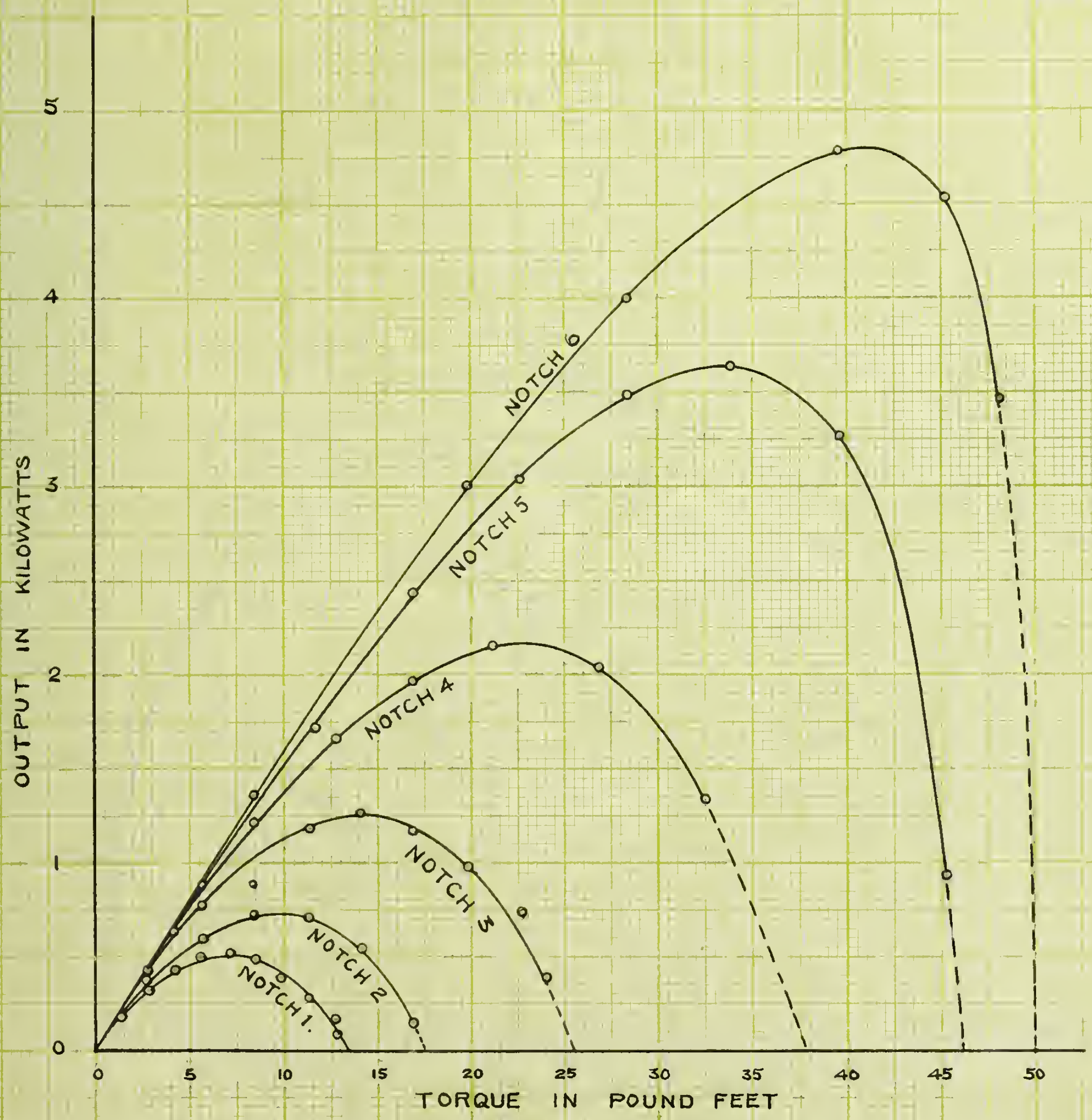
OPERATION CURVES NOTCH 5.



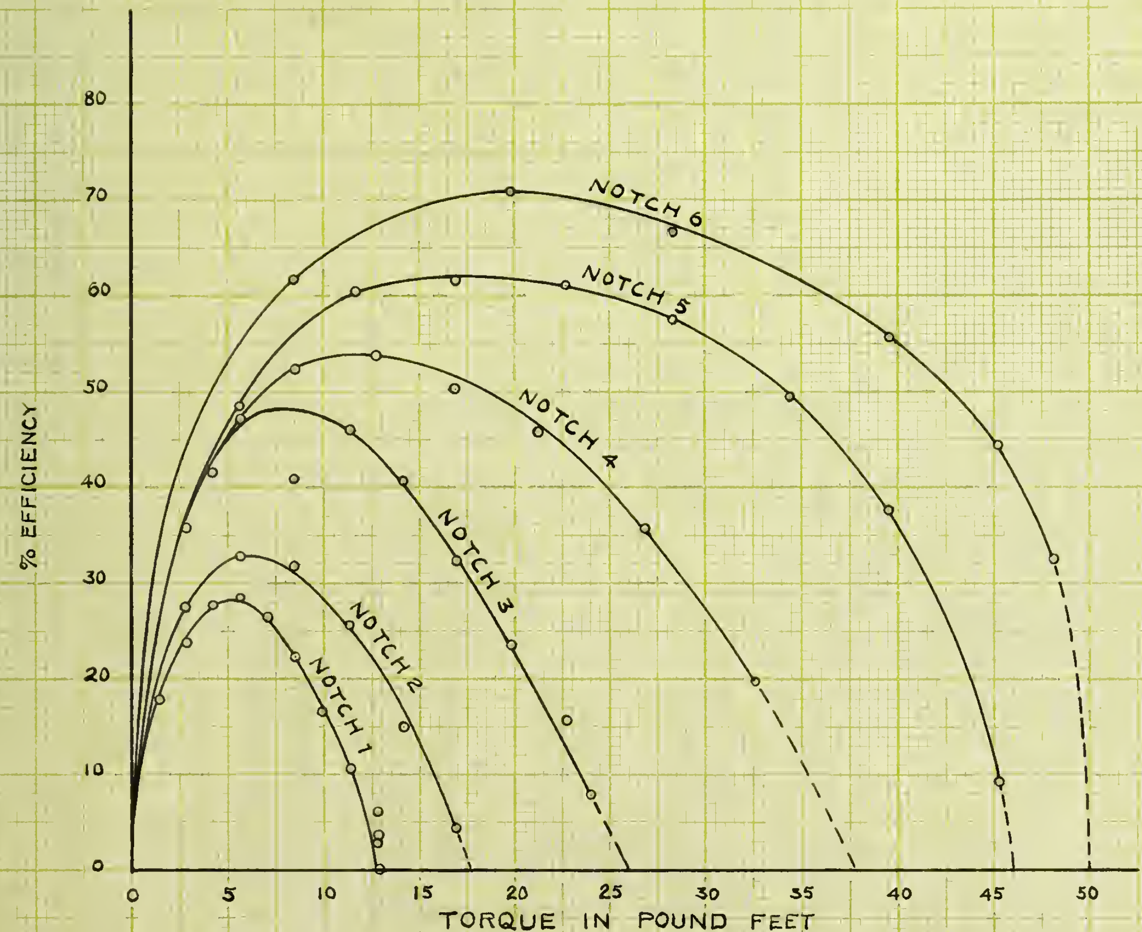
OPERATION CURVES NOTCH 6.



ASSEMBLED SPEED CURVES



ASSEMBLED OUTPUT CURVES.



ASSEMBLED EFFICIENCY CURVES.

ROTOR RESISTANCE

RING to RING

Temp.	A to B	B to C	A to C
24°C	0.0103	0.0093	0.0103
Hot	0.0143	0.0117	0.0134

BRUSH RESISTANCE RUNNING HOT = 0.0047 OHMS.

STATOR RESISTANCE

Temp.	PHASE A	PHASE B
24°C	0.1820	0.1810
Hot	0.1954	0.1957

IRON RESISTANCES

NOTCH	A to B = F to D		B to C = D to E		A to C = F to E	
	24°C	100°C	24°	100°	24°	100°
1	0.340	0.440	0.333	0.435	0.345	0.450
2	0.238	0.300	0.237	0.310	0.243	0.315
3	0.1443	0.188	0.144	0.188	0.146	0.190
4	0.075	0.097	0.076	0.099	0.077	0.100
5	0.0316	0.041	0.0286	0.0372	0.0307	0.040
6	0.0122	0.016	0.0054	0.0070	0.006	0.0078

RESISTANCES OF TYPE "F" MOTOR

IRON LOSSES.

E_a	I_a	W_a	$I_a^2R_a$	IRON LOSS$_A$	E_b	I_b	W_b	$I_b^2R_b$	IRON LOSS$_B$	TOTAL IRON LOSS	TOTAL COPPER LOSS	STATOR FREQ.	ROTOR FREQ.
110.4	10.95	116	23.5	92	109.7	10.72	116	22.5	93	185	46	60	20
110.4	10.85	71	23.0	47	109.7	10.60	71	22.0	49	96	45	60	0
110.4	10.95	106	23.5	82	109.7	10.72	106	22.5	83	165	46	60	60

STATOR IRON LOSS = 96 WATTS

ROTOR IRON LOSS, AT 60~, = 165 - 96 = 69 WATTS

ROTOR EDDY-CURRENT LOSS, AT 60~ = 185 - 165 = 20 WATTS

ROTOR HYSTERESIS LOSS, AT 60~ = 69 - 20 = 49 WATTS

ROTOR HYSTERESIS AT, "N", REV. PER MIN. = $49 \times \left(1 - \frac{N}{1200}\right)$

ROTOR EDDY CURRENT LOSS AT "N", R.P.M. = $20 \times \left(1 - \frac{N}{1200}\right)^2$

MOTOR FRICTION

No.	E_t	I_a	I_f	R.P.M.	$I_a^2 R_a$	STRAY POWER D.C.M	$E_t I_a$	FRICTION A.C. MOTOR	Torque
1	97.3	7.94	1.9	1190	7.3	186	579	772	3.42
2	92.3	7.94	1.9	1125	7.3	173	553	733	3.46
3	56.4	9.8	1.00	900	11.4	105	437	553	3.06
4	40.1	8.8	1.0	610	9.0	65	284	354	3.20
5	14.4	80	1.0	213	7.4	20	88	115	2.90

AVerag Torque = 2.41 lb.ft.

By extending Rotor Current Curve

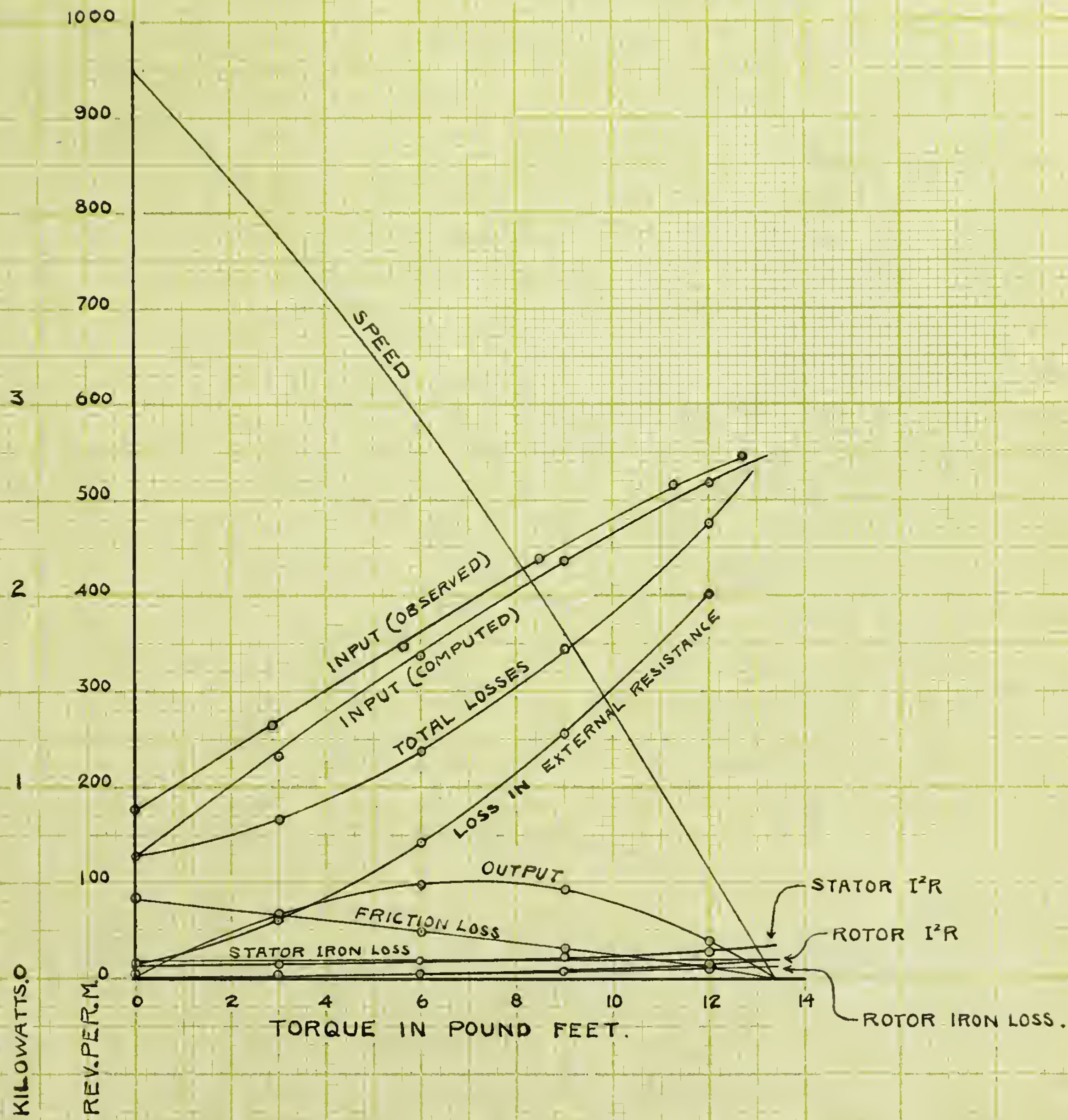
FRICTION TORQUE = 3 lb.ft.

No.	Torque	R.P.M.	Output	I_s	STATOR $I_s^2 R_s$	I_R	ROTOR COPPER	I^2R Ext. Res.	ROTOR Iron Loss	FRICTION LOSS	TOTAL LOSS	TOTAL INPUT	Eff. %
NOTCH 1.													
1	0	950	0	12.5	61	10.0	2	68	12	405	644	644	0
2	3	780	332	13.5	72	21.0	8	300	20	333	829	1161	28.6
3	6	583	496	15.0	88	32.3	21	710	30	2,50	1195	1691	29.3
4	9	360	460	16.4	106	43.4	37	1280	44	154	1717	2177	21.2
5	12	115	196	18.4	133	54.2	58	2000	60	50	2397	2593	7.5
NOTCH 2.													
1	0	1028	0	11.8	55	11.0	2.5	58	8	438	658	658	0
2	4	825	468	13.5	71	25.5	13	310	18	353	861	1329	35.2
3	8	620	705	16.2	103	40.0	32	762	29	265	1287	1992	35.4
4	12	403	687	19.0	142	55.0	60	1440	41	172	1951	2638	26.0
5	16	150	340	21.8	186	71.0	100	2400	58	64	2904	3244	10.5
NOTCH 3													
1	0	1085	0	11.9	56	11.3	2.5	38	5	462	659	659	0
2	6	924	786	14.3	80	34.0	23	345	13	395	952	1738	45.2
3	12	710	1210	17.8	124	56.8	64	955	24	304	1567	2777	43.6
4	18	440	1124	22.0	190	82.0	132	2000	39	188	2645	3767	34.4
5	24	115	392	28.8	325	110.5	242	3630	60	50	4403	4795	8.2

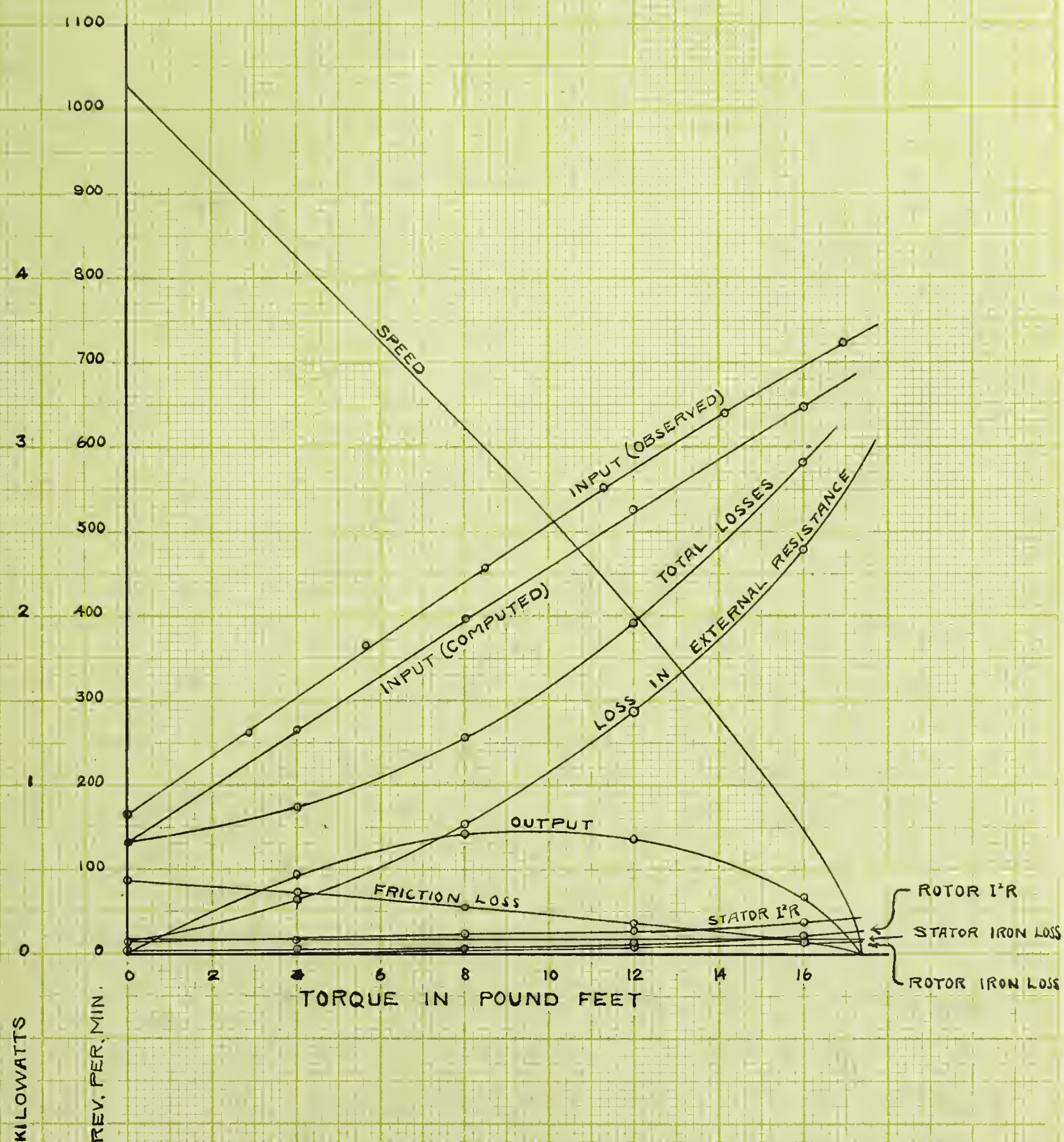
SEPARATION OF LOSSES

NOTCH 4.

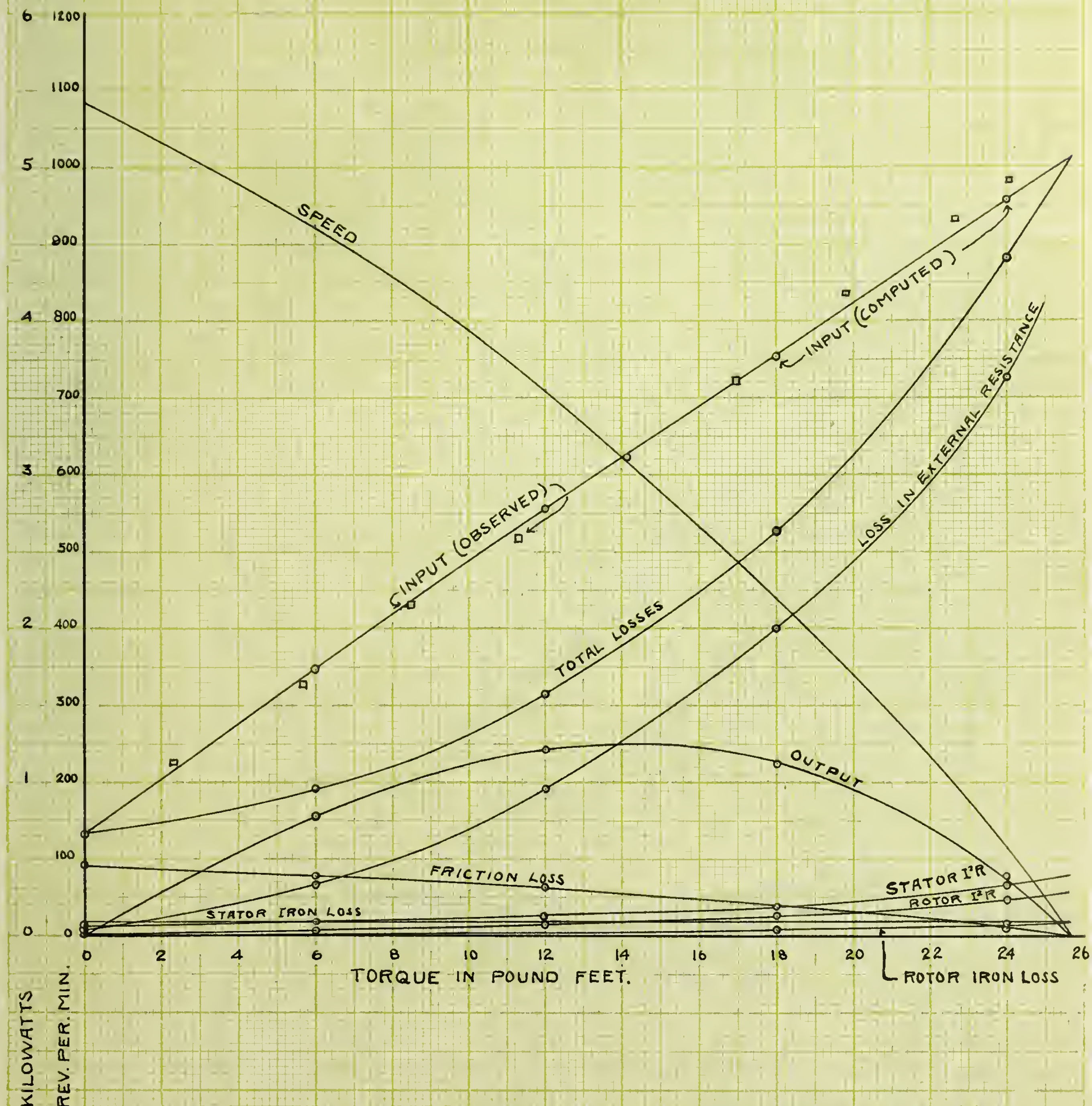
No.	Torque	R.P.M.	Output	I_s	$I_s^2 R_s$	I_R	ROTOR COPPER	I^2R Ext. Res.	ROTOR IRON LOSS	FRICTION LOSS	TOTAL INPUT	TOTAL INPUT	Eff. %
1	0	1140	0	10.9	47.0	11	2.4	20	3	485	653	653	0
2	8	1008	1145	16.0	100	42	35	287	9	430	957	2100	54.5
3	16	846	1920	22.0	190	74	108	890	17	360	1660	3580	53.7
4	24	635	2180	29.0	330	110	240	1970	28	272	2936	5120	42.6
5	32	320	1460	38	565	155	475	3400	47	136	5180	6640	22.0
		NOTCH 5.											
1	0	1178	0	11	48	11	2.4	9	1	500	656	656	0
2	10	1087	1540	18	127	50	50	184	5	462	924	2460	62.6
3	20	980	2780	24.8	340	93	170	635	10	420	1670	4450	62.5
4	30	833	3550	35	480	140	387	1440	18	355	278	6330	56.0
5	40	564	3200	51	1020	202	810	3000	32	240	5200	8400	38.1
		NOTCH 6											
1	0	1191	0	11.2	49	11	2.4	3.6	0.4	506	657	657	0
2	12	1115	1900	18.4	132	61	74	110	4.0	475	891	2791	68.0
3	24	1033	3520	27.3	292	115	260	392	8	440	480	5000	70.4
4	36	910	4650	41.0	660	181	650	970	14	390	2780	7425	62.6
5	48	507	3460	73.8	2130	300	1780	2660	35	215	6920	0380	33.4



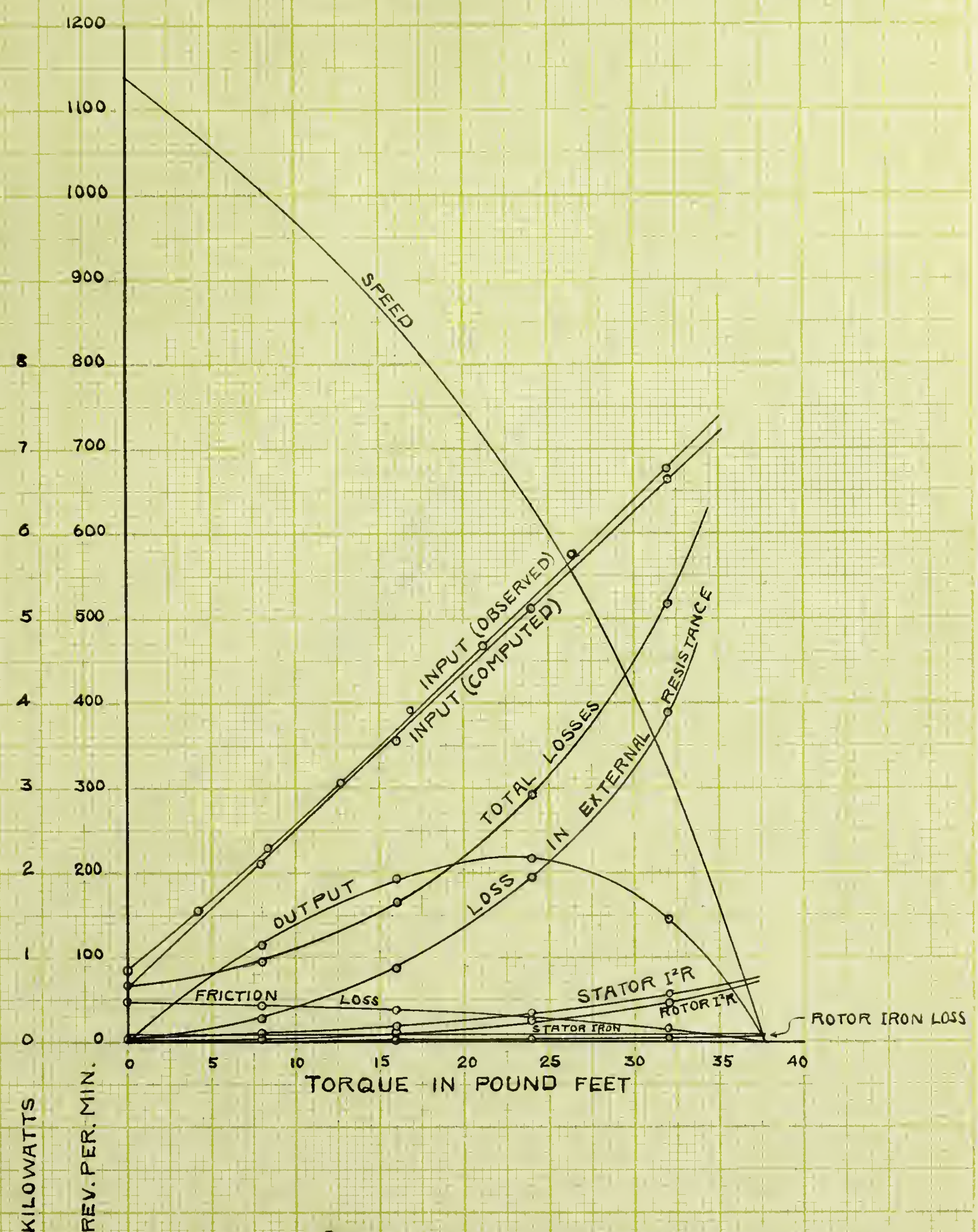
SEPARATION OF LOSSES NOTCH 1.



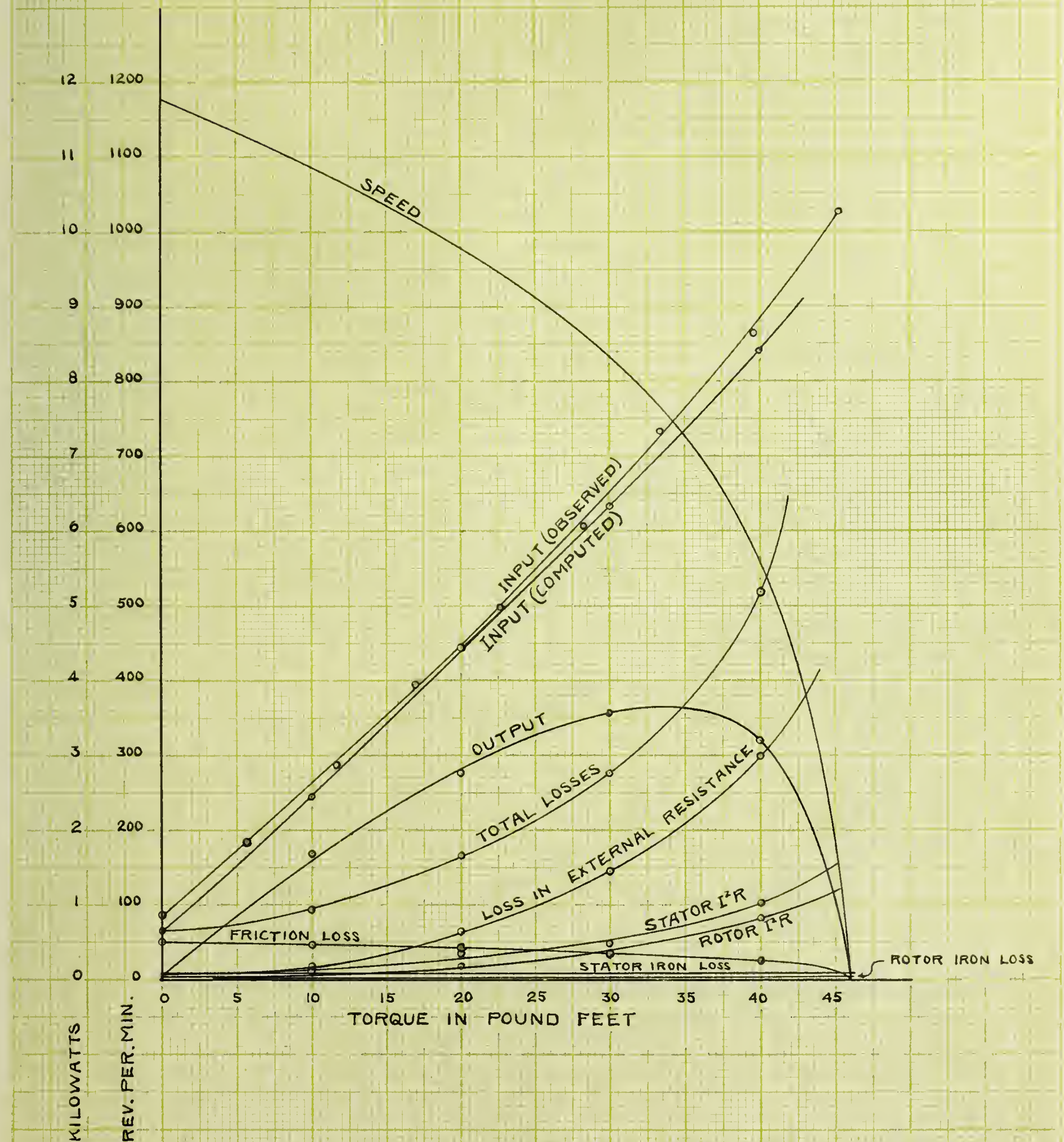
SEPARATION OF LOSSES NOTCH 2.



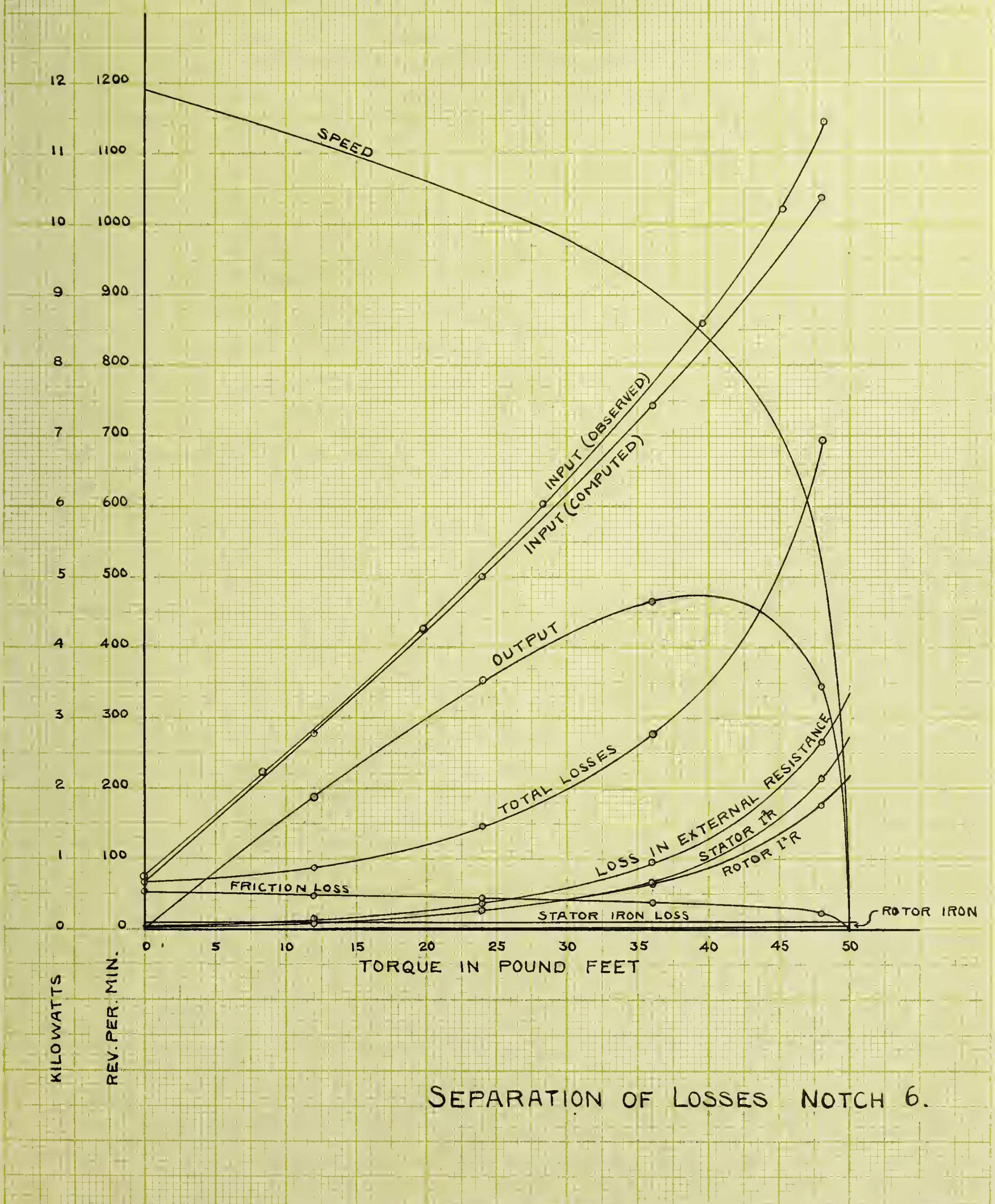
SEPARATION OF LOSSES NOTCH 3.



SEPARATION OF LOSSES NOTCH 4



SEPARATION OF LOSSES NOTCH 5.


12
11
10
9
8
7
6
5
4
3
2
1
0
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
SPEED
INPUT (OBSERVED)
INPUT (COMPUTED)
OUTPUT
TOTAL LOSSES
LOSS IN EXTERNAL RESISTANCE
STATOR I²R
ROTOR I²R
FRICTION LOSS
STATOR IRON LOSS
ROTOR IRON
0
5
10
15
20
25
30
35
40
45
50
TORQUE IN POUND FEET
KILOWATTS
REV. PER. MIN.
SEPARATION OF LOSSES NOTCH 6.